Routledge
Taylor & Francis Group

Creativity Research Journal

ISSN: 1040-0419 (Print) 1532-6934 (Online) Journal homepage: http://www.tandfonline.com/loi/hcrj20

Linkographic Evidence for Concurrent Divergent and Convergent Thinking in Creative Design

Gabriela Goldschmidt

To cite this article: Gabriela Goldschmidt (2016) Linkographic Evidence for Concurrent Divergent and Convergent Thinking in Creative Design, Creativity Research Journal, 28:2, 115-122, DOI: 10.1080/10400419.2016.1162497

To link to this article: http://dx.doi.org/10.1080/10400419.2016.1162497

CREATIVITY RESEARCH JOURNAL, *28*(2), 115–122, 2016

ISSN: 1040-0419 print/1532-6934 online
DOI: 10.1080/10400419.2016.1162497

Linkographic Evidence for Concurrent Divergent and Convergent Thinking in Creative Design

Gabriela Goldschmidt
Faculty of Architecture and Town Planning Technion – Israel Institute of Technology Haifa, Israel

For a long time, the creativity literature has stressed the role of divergent thinking in creative endeavor. More recently, it has been recognized that convergent thinking also has a role in creativity, and the design literature, which sees design as a creative activity a priori, has largely adopted this view: Divergent and convergent thinking are seen as occurring in cyclic phases within the design process. Neurological evidence suggests that frequent shifts between defocused and focused attention to stimuli in memory activation, which equate divergent and convergent thinking, are a hallmark of creative thinking. In this article, we use linkography to show that the shifts between divergent thinking—forelinking of design moves, and convergent thinking—backlinking of moves, are so frequent that at the cognitive scale they can be seen as occurring concurrently in the ideation phase of creative designing. It is proposed that in assessments of creative potential, shifts between divergent and convergent thinking should be the yardstick instead of, or alongside measurements of divergent thinking.

Many researchers subscribe to the view that people use two modes of reasoning, indeed two ways of thinking that serve them in everyday life, as well as in specialized problem solving. Different terms have been used to describe the two modes. In an overview paper, Evans (2008) pointed out that there are various theories of dual processing types, systems, or modes of reasoning, not all of which are compatible with one another, as their attributes cannot necessarily be mapped onto two generic categories of processing. Kahneman (2011), along with other researchers, sees them as fast and slow systems, respectively. The former is mostly intuitive, automatic, based on memory and emotion; the latter is reflective and rational, calculating consequences. Sloman (1996) talked about an associative, similarity-based system versus a symbolic, rule-based system. The associative system makes use of visuals when relevant (as in design); the rule-based system specifies rationale. Evans (e.g., 2008; Evans & Stanovich, 2013) described in detail the various theories and the attributes of the two systems, types or modes of processing, and responded to criticism launched against them, stressing that he does not assume the existence of two distinct systems, but rather of various combinations of attributes[1].

In the context of neurology, Gabora (2010) talked about associative thought and analytic thought wherein the former tends to be intuitive, divergent, and "conducive to unearthing remote or subtle associations between items that share features or are correlated but not necessarily causally related. This may lead to a promising idea or solution, although perhaps in a vague, unpolished form" (Gabora, 2010, p. 2). In contrast, analytic thought is rule-based and convergent, and is "conducive to analyzing relationships of cause and effect between items already believed to be related" (Gabora, 2010, p. 3). Basadur (1995) used the terms *ideation* and *evaluation* to describe the scope of the spectrum Gabora referred to, and related them to divergent and convergent thinking. Goel (2014) talked about lateral and vertical transformations in thinking that he explicitly identified with divergent and convergent thinking. Indeed, most researchers who described two reasoning and thinking modes used the terms

Correspondence should be sent to Gabriela Goldschmidt, Faculty of Architecture and Town Planning Technion – Israel Institute of Technology Haifa, Israel 32000. E-mail: gabig@technion.ac.il

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/HCRJ.

[1] Despite Evans and Stanovich's (Evans & Stanovich, 2013) analysis of the various terms and their preference for *types of processing*, I find *modes of thinking* more appropriate in the current discussion. However, I strongly disagree with these researchers' claim that *modes* are cognitive styles that are manifest within Type 2 thinking.

TABLE 1
Attributes of two modes of thinking

	Mode 1 (roughly Divergent)	*Mode 2 (Roughly Convergent)*
Basadur (1995)	Ideation	Evaluation
Sloman (1996)	Associative, similarity-based	Symbolic, rule-based
Gabora (2010)	Associative: intuitive	Analytic: rule-based
Kahneman (2011)	Fast: Intuitive, based on memory and emotion	Slow: Rational, calculating consequences
Goel (2014)	Lateral transformations	Vertical transformations

divergent and *convergent thought*; other appellations of dual thinking modes, such as systems and most commonly types, may be regarded as roughly corresponding to divergent and convergent thinking. Table 1 summarizes the examples cited previously. As mentioned, a more elaborate table can be found in e.g., Evans (2008).

DIVERGENT AND CONVERGENT THINKING

One of the many definitions of divergent thinking is "thinking that moves away in diverging directions so as to involve a variety of aspects and which sometimes lead[s] to novel ideas and solutions; associated with creativity" (*The Free Dictionary*, "Divergent thinking"). Convergent thinking is demarcated as "thinking that brings together information focused on solving a problem (especially solving problems that have a single correct solution)" (*The Free Dictionary*, "Convergent thinking"). A predominant neurological account of the two modes of thought hinges on memory activation patterns in the brain when attention is directed to stimuli. Gabora (2010) explained that divergent (associative) thought is based on defocused attention and convergent (analytic) thought is related to focused attention. Defocused attention corresponds to a high level of neuron activation and leads to a flat pattern, that is, activation is distributed across overlapping locations in the relevant region of neurons. Conversely, in focused attention, memory locations are activated that are farther from one another, resulting in a spiky pattern. Shifts between focused and defocused attention are controllable, unlike many other aspects of memory activation. Goel (2014) advanced another, but compatible, explanation, based on different transformations that occur in the right and left prefrontal cortex. Lateral transformations support divergent thinking, whereas vertical transformations sustain convergent thinking. In support of this assertion, Goel cited an fMRI study by Ellamil, Dobson, Beeman, and Christoff (2012), which compared generative (divergent) and evaluative (convergent) phases of creative design. The results confirm Goel's claim.

The interest in divergent and convergent thinking originates mainly from the study of creativity, wherein for a long time divergent thinking got, and still gets, the lion's share of attention, as it has been seen as the hallmark of creative thinking (e.g., Finke, Ward, & Smith, 1992; Mednick, 1962). Many psychometric creativity tests also center on divergent thinking (e.g., Torrance, 1974, 1988); as put by Plucker and Renzulli (1999): "Divergent thinking tests historically occupy nearly the entire creative process spotlight" (p. 41). Now there is a new generation of divergent thinking tests (e.g., Auzmendi, Villa, & Abedi, 1996; Urban & Jellen, 1996) that unpack divergent thinking into its constituent attributes such as fluency, originality, flexibility, and elaboration (Runco & Acar, 2012). Today, however, there is a wide acceptance that creativity demands not only divergent thinking, but also convergent thinking, which is not extensively studied. In this article, we treat both divergent and convergent thinking holistically, with no regard to their attributes, whose study belongs in a different framework.

CREATIVITY INVOLVES DIVERGENT AND CONVERGENT THINKING

Researchers who acknowledge the need for both divergent and convergent thinking often propose that they encompass discrete phases of creative processes (e.g., Ichino, 2011). Runco (1991) observed: "The evaluative [convergent] component of the creative process has received very little attention, … This is surprising because it is a vital constituent of the creative process, and is required whenever an individual selects or expresses a preference for an idea or set of ideas" (p. 312; see also Runco, 2007; Runco & Acar, 2012). Goel (2014) is of the same opinion. Vidal (2010) quoted Leonard and Swap (1999), who described the creative process (in groups) as comprising five steps, of which the third is divergence: generating options, and the fifth is convergence: selecting options (step four in between is incubation). However, Vidal acknowledged that the process involves "cycling repeatedly through a process of divergent and convergent thinking" (p. 412). In design, the dual mode has been a prominent view, embedded in various models of the design process (e.g., Cross, 1994; Fricke, 1996; Pugh, 1991; Roozenburg & Eekels, 1995).

The notion of repeated cycling between the two modes of thinking has been gaining increasing support in the work of leading researchers. Perkins (1981) proposed intuitive and analytical processes in creative thought, which are equivalent to divergent and convergent thought, and added that "the two strategies could occur mixed in behavior" (p. 105), despite the fact that they are usually discussed separately. He went on to state that "inventive people are mode shifters [between divergent and convergent thinking]" (Perkins, 1992, p. 249). Gruber, a renowned creativity scholar who studied the lives of prominent creative individuals, rejected the emphasis on single inspirational moments and looked, instead, at "many moments of insight that occur in the course of a creative effort" (Gruber & Davies, 1988, p. 244). Elsewhere, Gruber (1980) said, "Interesting creative processes almost never result from single steps, but rather from concatenations and articulation of a complex set of interrelated moves." (p. 177). As mentioned earlier, Gabora (2010) turned to neuroscience to shed light on creative thinking, and concluded that mode-shifting is essential to creativity. Runco and Basadur (1993) stressed the need for both ideational skills (divergent thinking) and evaluative accuracy (convergent thinking), in addition to appropriate attitudes, in creative performance. They also believed that skills and accuracy can be improved by training. Basadur, Wakabayashi, and Graen (1990) endorsed the view that creativity is multifaceted and added, "Creative problem solving is a complete *process* involving several particular phases synchronizing divergent and convergent thinking in each phase" (p. 166). Linhares, Freitas, Mendes, and Silva (2012), who studied chess playing, found evidence that pattern recognition and *rational forward search*, which are not far from convergent and divergent thinking, respectively, are deeply entangled, which may suggest a similar entanglement of systems in other instances of problem-solving thinking, such as designing.

In the design literature, Tversky and Chou (2010) took it for granted that thinking both divergently and convergently is needed to succeed in designing. Liu, Blight, and Chakrabarti (2003) advanced the notion of *multiple divergence-convergence* throughout the design process, and Dong (2007) talked about *cycles of convergence and divergence* on the way to a coherent design concept. Dym, Agogino, Eris, Frey, and Leifer (2005) argued that design thinking entails inquiry that "includes both a convergent component … and a divergent component" (p. 105). This inquiry is "an iterative loop of divergent-convergent thinking" (p. 104). The expanse of cycles of divergent and convergent thinking differs in the various studies, but no specific extents are indicated. None of the researchers went as far as suggesting instantaneous shifts between the two modes of thinking. In what follows, we propose that the two modes of thinking occur virtually concurrently in the design process, and we use linkography to explicate this proposal.

LINKING DESIGN MOVES FORWARD AND BACKWARD CORRESPONDS TO DIVERGENT AND CONVERGENT THINKING

To study the process of design thinking, one must capture it with high fidelity. The closest researchers can approach it is by documenting verbalizations of designers during the process of designing. This is precisely the procedure in *protocol analysis*: A group conversation or an individual thinking out loud is recorded; the recording is transcribed and then parsed into segments that become the units of analysis. If one is interested in the cognitive scale, these units are rather small—I call them *design moves*. In the case of an individual, the average length of a design move is around 7 sec (Goldschmidt, 2014). In regular protocol analysis studies, moves (or other segments) are encoded according to a scheme of categories and the results are submitted to analysis. I choose to treat protocols differently: I look at links that moves form among each other. This approach is in line with Gruber's claim that creative processes hinge on a complex set of interrelated moves (1980). The question: "Is there a link?" is asked for every pair of moves; for n moves it is asked $n \times (n - 1) / 2$ times. The basis for judging whether a link exists is the contents of the two moves, and the judgment is made using common sense and sufficient expertise regarding the discipline and the design task. Links are notated in a graph called a *linkograph* (e.g., Goldschmidt, 1995, 2014); see Figure 1.

When establishing links, researchers match each move with every preceding move to determine whether a link between them exists. A link that is thus established is called a *backlink*, as it points back in time—one links backward from a given move to a move made earlier in time. After the fact, one may talk about a virtual forelink between the earlier move and the current move, which is made later in time. For example, if a researcher finds a link between move m and an earlier move j, it will be m's backlink to j. The same link is move j's forelink to move m. Forelinks are virtual because at the time that the earlier move (e.g., move j) is generated, no subsequent moves are in existence yet, and therefore one cannot know in real time whether or not move j will be linked to a later move (e.g., move m). However, with hindsight, one can talk about forelinks. Researchers treat real (assessed) backlinks and virtual (derived) forelinks as equals. Forelinks are of great significance, as I show presently. Here is an example.

Figure 1 shows a linkograph in which only the links generated by move 5 (backlinks and forelinks) are notated. It pertains to a vignette from a team design process of a bicycle rack for a specific backpack, generated for the Delft Protocol Workshop (Cross, Christiaans, & Dorst, 1996). The transcript of the linked moves reads as follows:

> *Move 5* 'Cos it would be nice I think I mean just from a positioning standpoint if we've got this frame outline and we know that they're gonna stick with that you can vacuum form a tray or a

In move 5 the rack's description as a tray is confirmed, after the team had considered other solutions (bag, net with a drawstring, etc.). The tray concept, or metaphor, first proposed in move 3, guided the further development of the design. Move 5 links back to moves 3 and 4 (which have forelinks to move 5):

> *Move 3* So it's either a bag or maybe it's like a little vacuum-formed tray kinda for it to sit in

> *Move 4* Yeah a tray that's right

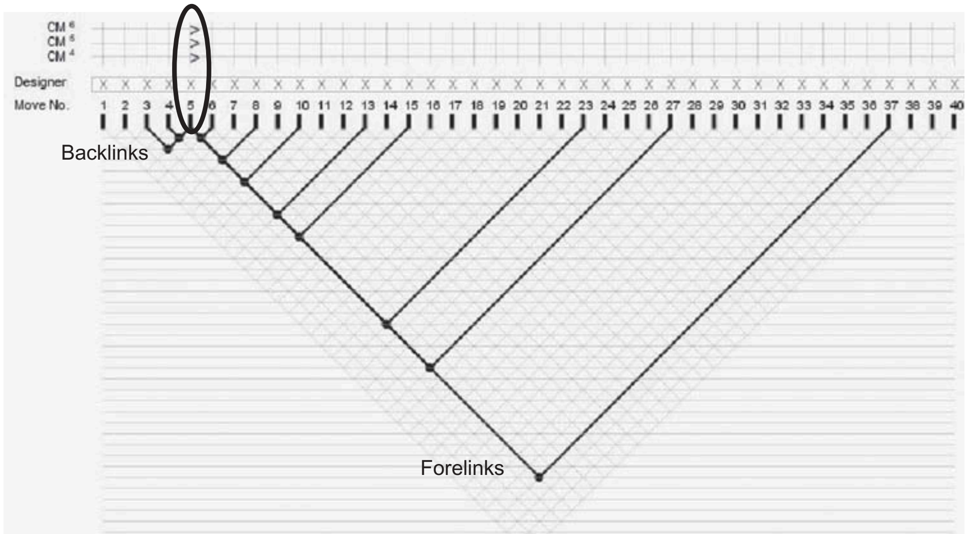

FIGURE 1 Backlinks and forelinks of move 5 notated in a linkograph.

Move 5 forelinks to moves 6, 8, 10, 13, 15, 23, 27 and 37 (which, in turn, link back to move 5):

> *Move 6* Right, or even just a small part of the tray, or I guess they have these
>
> *Move 8* Maybe the tray could have a plastic snap features in it so you just like kkkk snap your backpack down in it
>
> *Move 10* It's a multifunction part huh
>
> *Move 13* It takes care of the easy it takes care of the rooster tail problem of your pack
>
> *Move 15* Maybe it could be part maybe it could be a tray with a with net and drawstring on the top of it
>
> *Move 23* So what we're doing right now, though, is we're coming up with, like again, classifications of solutions of kind of all; they're all either/or things; I mean we wouldn't do the net and the shade and the snap in with the tray; either or any one of those probably
>
> *Move 27* I think tray is sorta a new one on the list it's not a subset of bag; it's kind of er yeah but oh yeah yeah yeah oh I see shade straps is how do you dress the straps on the back
>
> *Move 37* You have a the tray would zip clip

One can see that in this vignette, move 5 has two backlinks and eight forelinks. One can establish a threshold number of links (e.g., six links, but never fewer than three links), and moves that reach at least this number of links either forward or backward are called *critical moves* (CMs). We distinguish between CMs due to a large number of backlinks (<CMs) and Cms owing to a large number of forelinks (CMs>). In rare cases, a move is found that boasts a large number of links in both directions (<CM>). Critical moves are of special interest because they are prime contributors to a high level of interconnectivity of moves, which is how a design synthesis is achieved. The threshold for the establishment of criticality is flexible and depends on the nature of the study. In the linkograph in Figure 1 note that above move 5, a forward mark (>) is indicated at the level of CM^4, CM^5 and CM^6, that is, at thresholds of four, five, and six forelinks. Because the move has eight forelinks, the same mark would appear if the CM lines were calibrated to include that threshold level.

I claim that forelinks are manifestations of divergent thinking and backlinks are indications of convergent thinking (Goldschmidt, 2014). This is exemplified in the vignette from the bicycle rack design, which shows that backlinks stand for appraisal, evaluation, and confirmation. In contrast, forelinks stand for steps forward, the consideration of more options and possible solutions, further development. The observed duality shows that in creative design both divergent and convergent thinking are needed. I subscribe to the claim that they occur all but concurrently. To illustrate this claim, this study concentrates on CMs because they are the most significant moves in a design process: If one believes that links among moves create the network that leads to a design synthesis, then it follows that moves with a large number of links, that is, CMs, are of special importance. To test the notion that convergent and divergent thought in creative design are contemporaneous, we advance the following two propositions:

> Proposition 1: A process of designing that is considered creative displays a balance between CMs due to a high number of forelinks and CMs due to a high number of backlinks.

Proposition 2: CMs have a majority of links in the direction that corresponds to their designated criticality (forward or backward), but they also have links in the opposite direction.

The next section presents evidence from empirical studies to support these propositions.

EMPIRICAL EVIDENCE

Data from several empirical studies are used to report findings that pertain to the ratio of <CMs to CMs>, and the percentage of backlinks and forelinks within the two kinds of critical moves. The data are derived from Goldschmidt (2014).

Ratio of <CMs to CMs>

The two main studies used are the aforementioned Delft bicycle rack design and a study conducted at MIT, in which individual participants looked at the impact of different optional entry locations on the design of a small library. The participants were architects and architecture students of various standing, including some highly regarded experts.[2] The Delft designers, an individual mechanical engineer and a team of three industrial designers, were all experts (Cross, 2011). I use cumulative mean values, as well as particular cases, to exemplify my stance.

Table 2 lists proportions of <CMs and CMs> at a number of thresholds in various studies. Note that the proportions vary somewhat across thresholds. It is important to note that the total number of critical moves in a sequence can make a difference; if this number is very low, the results may be skewed.

Due to the different thresholds and different lengths of sequences (lengths of protocols), I cannot average the percentages in Table 2, but with the exception of one case, MIT Gideon, the proportions tend to be quite balanced, with more CMs> than <CMs in most cases (MIT Glenda is an exception). Gideon, a graduate student who participated in the MIT study, generated far more CMs> than <CMs. Not surprisingly, he was one of two weak and uncreative designers (see Goldschmidt, 2014). The exceptions Gideon and Glenda were also the ones with the lowest number of CMs, which may have affected their results. If one looks at the cumulative result across various studies, one finds that the ratio of CMs> to <CMs comes close to 60:40, which is also the ratio found for Martin, a prominent European architect, and which resembles the ratio in most other studies. This suggests that in creative design, one finds more divergence than convergence but the proportions, which appear to remain rather stable, also boast a fair amount of convergence.

We can further inspect CMs>:<CMs ratios by looking at the performance of the members of the Delft team (lines 1 and 2 in Table 2), Kerry, Ivan and John. Table 3 gives this information, for two criticality thresholds: six and seven links.

For team members Ivan and John, the ratios revealed in Table 3 resemble and corroborate those in Table 2 (Delft team). At the level of CM^6, their ratios are close to 60:40. At the high level of CM^7 the proportions are less clear-cut, but CM^7s> still prevail over <CM^7. Kerry is an exception: She makes more <CMs than CMs>, at a similar, but reversed ratio (in this, she resembles Glenda in Table 2). Her performance in this vignette is explained elsewhere, as part of an account of the team's work (Cross & Clayburn Cross, 1995). Here the data are used to further strengthen the finding that, in most cases, divergent and convergent thinking, as manifest in CMs> and <CMs, tend to be rather balanced, with an advantage to divergent thinking. This advantage is typical of the idea generation phase of design, and more generally of "work classified as more problem finding in nature" (Basadur, 1995, p. 63). Overall, these findings confirm proposition 1.

TABLE 2
Ratio of CMs> to <CMs

Study	*Threshold*	*CMs*	*%CM>*	*% <CM*
Delft team	CM^6	71	54	46
Delft team	CM^7	37	57	43
Delft individual	CM^7	14	57	43
MIT Glenda	CM^4	9	44	56
MIT Martin	CM^4	10	60	40
MIT Gideon	CM^4	8	87	13
Across various studies*	—	225	59	41

* 'Various studies' also include results from additional studies, not articulated here.

[2] The study was headed by Donald Schön and William Porter in the Architecture Department at MIT, with the support of National Science Foundation grant #8611357-DMC.

Distribution of Links Generated by CMs

Thus far, I have looked at CMs only in terms of the direction that won them criticality. However, in addition to links in the dominant direction, most critical moves (and moves in general) also have links in the opposite, nondominant direction. For example, move 5 in Figure 1 is critical owing

TABLE 3
Contribution of CMs> and <CMs by Team Members

Team member	*CM^6s*	*%CM>*	*%<CM*	*CM^7s*	*%CM>*	*%<CM*
Kerry	23	43	57	11	45	55
Ivan	33	58	42	12	67	33
John	30	57	43	20	55	45

* Protocol units 32–37.

TABLE 4
Distribution of links in CMs

Study	*Threshold*	*CMs>*	*% links>*	*% <links*	*<CMs*	*% <links*	*% links>*
MIT	CM4	24	76	24	12	76	24
Delft Indiv. (sample)	CM7	11	78	22	8	80	20
Delft team (sample)	CM7	33	77	23	28	80	20
Additional study 1*	CM6	28	81	19	16	79	21
Additional study 2*	CM6	34	83	17	26	82	18
Additional study 3*	CM7	3	74	26	2	83	17
Total	—	133	79	21	92	80	20

*Additional studies were carried out by graduate students as part of their theses at Technion and at TUDelft.

to eight forelinks, but it also has two backlinks. I now look at the proportion of links that critical moves generate in both directions. Table 4 presents data from several studies, using various criticality thresholds.

What these results tell is very interesting. When a move is generated that has many forelinks, it is designated as a CM>. However, it also generates backlinks: Around 80% of the move's links are forelinks and the remaining 20% are backlinks. Move 5 in Figure 1 is an example of this ratio, with eight forelinks and two backlinks. Likewise, a move that is defined as a <CM has a majority of backlinks, but also some forelinks, and here too the ratio is 80:20. This means that although a designer or a design team ideates, that is, comes forth with a new idea that would be further developed in subsequent moves (which backlink to it), the designer reserves some attention to evaluative activity and affirm (or question) what has already been done. Similarly, when the designer is busy analyzing and assessing something that has already been suggested, some of the attention is set aside to envision future development and new options. If one accepts the notion that forelinks, which are virtual, are as valid as directly assessable backlinks, then these results are evidence of the concurrence of divergent and convergent consideration in design thinking. The designer plans ahead while also making sure that continuity with past development is maintained; he or she ascertains that prior work is valid while preparing for more development. The integrity of the design effort is thus upheld while the effort to arrive at the best and most novel possible solution continues. The results presented in this section confirm proposition 2.

DISCUSSION

Current literature says that in creative work, and design in particular, frequent shifts between divergent and convergent thinking are necessary. From a neurological point of view, such shifts can occur if the mind is flexible enough to oscillate between focused and defocused attention to stimuli (Gabora, 2010). Focused attention is paid to what is already there, which in linkographic terms translates to links backward. Defocused attention allows attention to wander, to imagine what is not yet there, what may be possible. In linkography, this translates to links forward. Linkography makes it possible to measure these modes of thought by counting critical moves and their links in both directions. I have illustrated that in the conceptual stage of design problem solving, there is more divergent thinking than convergent thinking, with a ratio of up to 60:40, but both modes are present throughout the process. The preference for divergent thought is not surprising, given the fact that I focussed on the early idea-generation phase of designing, which is considered to be the most creative part of the design process. This phase is commonly seen as one in which problems are structured and defined, in parallel to the generation of solution ideas (Dorst & Cross, 2001). Accordingly, more ideation, that is, divergent thinking, is expected (Basadur, 1995). Furthermore, I have shown that in a thinking unit like a move, lasting about 7 sec, the two modes of thinking coexist. Most of the attention—80%—is invested in one mode of thinking, divergent or convergent, but part of it—the remaining 20%—is concurrently reserved for the other, complimentary mode, to ensure that the design holds together and progress is safeguarded.

The interest in divergent thinking as a major indicator, or predictor, of creative potential has led to research of its attributes and their measurement, which continues today. Convergent thinking has elicited much less interest as it was, and sometimes still is, seen as mundane and of little consequence for creativity. Historically, the study of divergent thinking started before neuroscience and neurocognitive science have illuminated the two modes of thinking from a different perspective, and at a different scale, involving much smaller thinking units. Linkography is a simple method that allows one to map the structure of design thinking in terms of networks of moves and links among them. Given the short duration of moves, the scale researchers work at is somewhere between whole phases of creative work and the neurocognitive scale of milliseconds. Because I equate the linking among design moves to manifestations of divergent and convergent thinking, I can measure them without recourse to their attributes. If one coded moves, or links (or both), with category schemes that pertain to attributes of thinking, one could also elaborate on those attributes. However, I believe that the manifestations of attributes are largely contingent on extraneous factors such as individual differences and especially the nature of the task, and therefore this study excludes allusion to attributes.

In a time unit of a few seconds like a design move, the concurrence of divergence and convergence suggests that neurocognitive tools are required to articulate further the remarkable mode shifting mechanism that is activated when creative designing takes place. As a result, it is proposed that instead of focusing on the measurement of divergent thinking to assess creativity, or alongside such measurements, researchers should start measuring shifts between divergent and convergent thinking, at least as far as design thinking is concerned but probably in other creative activities, as well. At the cognitive scale at which the work in this study is presented, I have shown elsewhere that in design, shifts between modes of thinking specified in terms of embodiment (physical attributes) and rationale (reasons for choice of attributes) are very frequent (Goldschmidt, 2013). It is time now to show that shifts between divergent and convergent thinking at the neurocognitive scale are so frequent that at the slightly slower cognitive scale, these two modes of thinking may be considered concurrent. It is hoped that collaborative work between researchers in design and neurocognitive science, like that pioneered by researchers like Goel (2014) and Ellamil et al. (2012), will continue to elucidate this intriguing human capacity.

ACKNOWLEDGMENT

An initial draft of this research presented at the *International Conference on Human Behavior in Design*, October 14-17, 2014, Ascona, Switzerland, and was published in the compendium of conference papers (no page numbers).

REFERENCES

Auzmendi, E., Villa, A., & Abedi, J. (1996). Reliability and validity of a newly constructed multiple-choice creativity instrument. *Creativity Research Journal*, *9*, 89–95. doi:10.1207/s15326934crj0901_8

Basadur, M. S. (1995). Optimal ideation-evaluation ratios. *Creativity Research Journal*, *8*, 63–75. doi:10.1207/s15326934crj0801_5

Basadur, M. S., Wakabayashi, M., & Graen, G. B. (1990). Individual problem solving styles and attitudes toward divergent thinking before and after training. *Creativity Research Journal*, *3*, 22–32. doi:10.1080/10400419009534331

Cross, N. (1994). *Engineering design methods—Strategies for product design*. Chichester, UK: John Wiley.

Cross, N. (2011). *Design thinking: Understanding how designers think and work*. Oxford, UK: Berg.

Cross, N., Christiaans, H., & Dorst, K. (Eds.). (1996). *Analysing design activity*. London, UK: John Wiley.

Cross, N., & Clayburn Cross, A. (1995). Observations of teamwork and social processes in design. *Design Studies*, *16*, 143–170. doi:10.1016/0142-694X(94)00007-Z

Dong, A. (2007). The enactment of design through language. *Design Studies*, *28*, 5–21. doi:10.1016/j.destud.2006.07.001

Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem–solution. *Design Studies*, *22*, 425–437. doi:10.1016/S0142-694X(01)00009-6

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *94*, 103–120. doi:10.1002/jee.2005.94.issue-1

Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. *NeuroImage*, *59*, 1783–1794. doi:10.1016/j.neuroimage.2011.08.008

Evans, J. S. B. T. (2008). Dual processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology*, *59*, 255–278. doi:10.1146/annurev.psych.59.103006.093629

Evans, J. S. B. T., & Stanovich, K. E. (2013). Dual-process theories of higher cognition: Advancing the debate. *Perspectives on Psychological Science*, *8*, 223–241. doi:10.1177/1745691612460685

Finke, R. A., Ward, T. B., & Smith, S. M. (1992). *Creative cognition: Theory, research, and application*. Cambridge, MA: MIT Press.

The Free Dictionary. (n.d.). Divergent thinking. http://www.thefreedictionary.com/divergent+thinking. Accessed January 25, 2015.

The Free Dictionary. (n.d.). Convergent thinking. http://www.thefreedictionary.com/convergent+thinking. Accessed January 25, 2015.

Fricke, G. (1996). Successful individual approaches in engineering design. *Research in Engineering Design*, *8*, 151–165. doi:10.1007/BF01608350

Gabora, L. (2010). Revenge of the 'neurds': Characterizing creative thought in terms of the structure and dynamics of memory. *Creativity Research Journal*, *22*(1), 1–13. doi:10.1080/10400410903579494

Goel, V. (2014). Creative brains: Designing in the real world. *Frontiers in Human Neuroscience*, *8*(Article 241), 1–14. doi:10.3389/fnhum.2014.00241

Goldschmidt, G. (1995). The designer as a team of one. *Design Studies*, *16*, 189–209. doi:10.1016/0142-694X(94)00009-3

Goldschmidt, G. (2013). A micro view of design reasoning: Two-way shifts between embodiment and rationale. In J. M. Carroll (Ed.), *Creativity and rationale: Enhancing human experience by design* (pp. 41–55). London, UK: Springer Verlag.

Goldschmidt, G. (2014). *Linkography: Unfolding the design process*. Cambridge, MA: MIT Press.

Gruber, H. (1980). Afterword. In D. H. Feldman (Ed.), *Beyond universals in cognitive development* (pp. 177–178). Norwood, NJ: Ablex Publishing Corp.

Gruber, H. E., & Davies, S. N. (1988). Inching our way up Mount Olympus: The evolving-systems approach to creative thinking. In R. J. Sternberg (Ed.), *The nature of creativity* (pp. 243–270). New York, NY: Cambridge University Press.

Ichino, J. (2011, September 24–28). Discriminating divergent/convergent phases of meeting using non-verbal speech patterns. In S. Bødker, N. O. Bouvin, W. Lutters, V. Wulf, & L. Ciolfi (Eds.), *ECSCW 2011: Proceedings of the 12th European conference on computer supported cooperative work* (pp. 153–172). Aarhus, Denmark: Springer Verlag.

Kahneman, D. (2011). *Thinking, fast and slow*. New York, NY: Farrar, Straus and Giroux.

Leonard, D., & Swap, W. (1999). *When sparks fly: Harnessing the power of group creativity*. Boston, MA: Harvard Business School Press.

Linhares, A., Freitas, A. E. T. A., Mendes, A., & Silva, J. S. (2012). Entanglement of perception and reasoning in the combinatorial game of chess: Differential errors of strategic reconstruction. *Cognitive Systems Research*, *13*, 72–86. doi:10.1016/j.cogsys.2010.12.006

Liu, Y.-C., Blight, T., & Chakrabarti, A. (2003). Towards an 'ideal' approach for concept generation. *Design Studies*, *24*, 341–355. doi:10.1016/S0142-694X(03)00003-6

Mednick, S. (1962). The associative basis of the creative process. *Psychological Review*, *69*, 220–232. doi:10.1037/h0048850

Perkins, D. (1981). *The mind's best work*. Cambridge, MA: Harvard University Press.

Perkins, D. (1992). The topography of invention. In R. J. Weber, & D. N. Perkins (Eds.), *Inventive minds: Creativity in technology* (pp. 238–250). New York, NY: Oxford University Press.

Plucker, J. A., & Renzulli, J. S. (1999). Psychometric approaches to the study of human creativity. In R. J. Sternberg (Ed.), *Handbook of creativity* (pp. 35–61). Cambridge, UK: Cambridge University Press.

Pugh, S. (1991). *Total design: Integrated methods for successful product engineering*. Reading, MA: Addison-Wesley.

Roozenberg, N. F. M., & Eekels, J. (1995). *Product design: Fundamentals and mthods*. Chichester, UK: John Wiley.

Runco, M. A. (1991). The evaluative, valuative and divergent thinking of children. *The Journal of Creative Behavior*, *25*, 311–319. doi:10.1002/jocb.1991.25.issue-4

Runco, M. A. (2007). *Creativity: Theories and themes: Research, development, and practice*. New York, NY: Academic Press.

Runco, M. A., & Acar, S. (2012). Divergent thinking as an indicator of creative potential. *Creativity Research Journal*, *24*, 66–75. doi:10.1080/10400419.2012.652929

Runco, M. A., & Basadur, M. (1993). Assessing ideational and evaluative skills and creative styles and attitudes. *Creativity and Innovation Management*, *2*, 166–173. doi:10.1111/caim.1993.2.issue-3

Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological Bulletin*, *119*, 3–22. doi:10.1037/0033-2909.119.1.3

Torrance, E. P. (1974). *The Torrance tests of creative thinking: Technical-norms manual*. Bensenville, Il: Scholastic Testing Services.

Torrance, E. P. (1988). The nature of creativity as manifest in its testing. In R. J. Sternberg (Ed.), *The nature of creativity: Contemporary psychological perspectives* (pp. 43–75). Cambridge, UK: Cambridge University Press.

Tversky, B., & Chou, J. Y. (2010). Creativity: Design and breadth. In T. Taura, & Y. Nagai (Eds.), *Design creativity 2010* (pp. 209–214). London, UK: Springer.

Urban, K. K., & Jelle, H. G. (1996). *Test for creative thinking-drawing production (TCT-DP). Lisse, Netherland*:. Swets and Zeitlinger.

Vidal, R. V. V. (2010). Creative problem solving: An applied university course. *Pesquisa Operacional*, *30*, 405–426. doi:10.1590/S0101-74382010000200009