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How Digital Tools Impact Convergent and Divergent Thinking in Design Ideation

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ABSTRACT

Digital tools that support creative activities are ubiquitous in the design industry, yet practitioners appear to prefer pen and paper for design ideation. To better understand this exception, we conducted a comparative study between analog and digital tools and their impact on the divergent and convergent thinking patterns of groups of designers. We analysed how 24 participants solved comparable design ideation tasks in two conditions using linkographic protocol analysis – a notation method that focuses on identifying and linking small steps in the design process called *moves*. Our findings suggest that digital ideation tools yield more convergent thinking compared to analog tools, with no discernible impact on general productivity or divergent thinking.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**; **Empirical studies in interaction design**.

KEYWORDS

Creativity, Divergent thinking, Convergent Thinking, Creativity Support Tools

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1 INTRODUCTION

The design industry is a heavily digitalised sector, with the majority of practitioners relying on digital tools for key activities such as wireframing, prototyping, and user testing[32]. This technological mediation of the creative process, however, is not uniformly distributed. The 2019 edition of the *Annual Design Tools Survey*[32] – a large-scale study of the toolkits used by designers across the world – indicates that one activity still resists digital transformation: 86% of respondents continue to use analog tools such as pen, paper, and whiteboards for brainstorming and ideation.

Human-Computer Interaction research at large has a tradition of introducing new digital tools to support local practices of computer users, and creativity studies within HCI are no exception: 62% of papers published between 1996 and 2015 included building new software and studying its influence on user behaviour [14]. An extended sample of these papers (adding the years 2016-2018) showed that, of all the design activities studied, ideation continues to attract the most attention, comprising 45% of all publications[13].

These two statistics – the continued use of analog tools by design practitioners and the continued development and study of digital tools in HCI – suggests a particular quality in ideation and brainstorming that remains problematic to mediate through technology. In order to isolate and reveal this quality, we present an in-depth comparative study between traditional analog tools and a digital system specifically designed to support the current practice of using sticky notes, whiteboards, and sketching. The analytic focus is on *divergent thinking* and *convergent thinking*, two processes which previous research literature has demonstrated are central components in creative problem solving[18, 34]. Its importance suggests that a better understanding of how digital and analog tools affect these cognitive processes may in turn help us understand designers' continued preference for analog tools in early-stage design ideation. Our approach is based on in-depth *linkography* [18] and *protocol analysis* [10] of team-based design, a method which produces a linkographic representation of a design session (see figure 1).

To this end, we ask the following exploratory research question is: *how do digital and analog tools influence divergent and convergent thinking in design ideation?*

We first position our work relative to two bodies of research: HCI research on Creativity Support Tool and creativity; and cognitive psychology research on divergent and convergent thinking. We then present our methodological approach, introducing the linkographic notation method [18] and explaining the design and procedure of the repeated-measure controlled experiment with 24 designers, where groups of three were asked to solve similar design tasks using either digital or analog tools. Using the linkographic representations of each group's ideation process, we present and discuss how the two conditions impacted their divergent and convergent thinking, specifically on three measures of these cognitive

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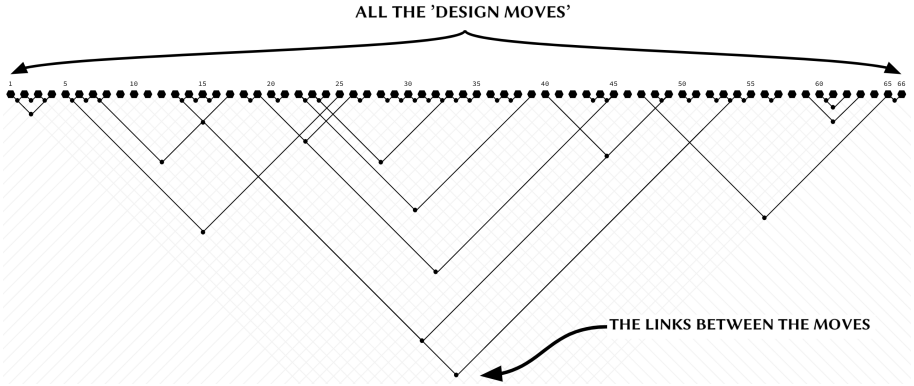

Figure 1: A Linkograph produced based on the analysis of a groups in the study

styles: backlinking critical moves, orphan moves, and the link index. Finally, we discuss what this implies for how designers can select tools to best match the intended outcome of design sessions, and for how we might develop tools that are suited for divergent thinking, convergent thinking, and combinations of the two.

2 RELATED WORK

The work presented in this paper speaks to creativity-related HCI research – specifically on *Creativity Support Tools* – and creativity-related cognitive psychology research. We will briefly review the status quo of each in turn.

2.1 HCI and digital tools for designers

Creativity-related HCI research emerged as a growing topic in ACM venues around the 2000s – when papers with creativity in the author keywords increased sixfold compared to the 1990s – and continued to grow in popularity in the 2010s [14]. The growth has been characterized by a strong focus on developing creativity support tools[13], with nearly half of all creativity-related papers reporting on a new piece of software built by researchers. The activities these tools support can be divided into six categories: pre-ideation or problem identification (10%), ideation (45%), evaluation or critique (18%), implementation (41%), iteration (6%), and project management or other meta activities (4%)[13].

Research on ideation, the activity in focus here, can be further distinguished based on the metric under investigation and the method used to gather and analyse the data. Metrics include, for example, the impact of design briefs [36], time constraints [2], or inspirational sources [21]; and the methods range between ethnographies [38], interviews [31], surveys [2], and ad-hoc user studies. The research relevant for this paper, reviewed below, lies at the intersection between studying the impact of tools (metric) and comparative experiments (method).

2.1.1 Tools for sketching. Tang et al. [40] Bilda and Dermikan [1], and Stones and Cassidy[37] all examined the impact of digital sketching tools on the design process using protocol analyses. Tang et al. [40] showed no difference between using an analog or digital sketching environment on the overall quality of the work (as rated by external judges). Bilda and Dermikan [1], on the other hand, concluded that analog pen and paper better supported the designers' perceptual activities in the process, leading to more exploratory attention shifts, a driving force behind iterating design concepts [39, 41]. Stones and Cassidy [37] compared Adobe Illustrator, Adobe Photoshop, and Macromedia Flash to pen and paper for sketching, but found no statistically significant impact on the choice of tool on "sketch reinterpretation": the reuse of sketches for new purposes. A more recent study by Jung et al. [27] compared Google Docs in distributed design contexts to pen and paper in co-located design, using thematic analysis of video recordings and transcripts. They concluded that the digital tool possessed the properties of simultaneity, shareability, visualizability, recordability; while the analog tool provided visibility, audibility, drawing ability.

2.1.2 Sticky notes and whiteboards. Whiteboards and sticky notes are a canonical design material and various HCI studies have explored and compared digital remediations of these tools. One of the early influential studies on was Klemmer et al.'s *Designers' Outpost* [28] published nearly twenty years ago, which presented a tangible interface for website design in the form of an electronic whiteboard augmented using computer vision to allow users to blend physical sticky-notes with digital media. The presented tool sought to use technology to address some of the potential drawbacks of the traditional analog setup in early phases of the web design process, while maintaining the benefits associated with its inherent tangibility.

Hilliges et al. [24] extended this line of research and investigated how to support collaborative creativity using an interactive digital table and large wall displays in face-to-face settings. The authors found that the number of ideas generated by the digital tools was comparable to a paper-based process, and that the perceived quality of ideas increased slightly.

Jensen et al. [26] recently contributed to this area of research by examining the effect of the particular material on the interaction patterns in collaborative ideation. The authors compared traditional, analog sticky notes to a digital implementation that was "[...] designed to be as close as possible to the physical setup of a collaborative ideation session, where users can use sticky notes, pens, and markers, and a (white)board". This was manifested in the final design through, for example, limiting the adhesive area of the digital sticky-notes to allow for stacking with other notes, and

constraining the available area for annotating and placing notes to the physical size of the large interactive display (i.e. no panning or zooming). The study found no difference in ideation-outcome based on number of notes created.

2.2 Convergent and Divergent thinking

The distinction between divergent and convergent thinking was originally proposed by Guilford [20] as two fundamentally different modes of problem-solving. Whereas divergent thinking is producing a diverse collection of ideas as the response to a question or a task, convergent thinking concentrates on narrowing down a collection of ideas to a single solution. Divergent thinking: "allows one to explore in different directions from the initial problem state, in order to discover many possible ideas and idea combinations that may serve as solutions" [12], whereas convergent thinking: "goes from an initial problem state through a series of prescribed operations in order to converge upon a single correct solution" [12, 30].

A common understanding of the development of the design process is that the first part of the process is of divergent nature, followed by a convergent period leading to the final design. Slightly more sophisticated design process models show that processes move through alternating phases of divergent and convergent nature, such as the common *Double Diamond* by The British Design Council [5] (see figure 2). Similar patterns can be found in many phase models of design, such as Ideo's Design Thinking process, in which divergence is described as "creating choices" and convergent thinking as "making choices" [25]. These models often refer to the overarching flow of an entire design project. However, these processes also unfold at the micro-level in design sessions, for instance when designers introduce, elaborate on, or discard ideas.

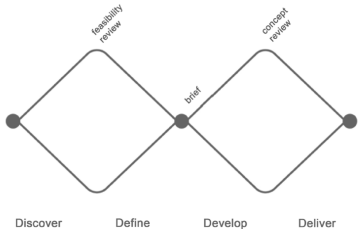

Figure 2: The Double Diamond model, which visualises the design process as moving through four phases of divergent, convergent, divergent, and convergent processes. [5]

Divergent thinking has been established as a key measure of creativity [35] and for instance been used by Warr and O'Neill [43] and by Gallagher [15] to investigate the effect of group composition on creativity. Although convergent thinking has received less attention, many designs and creativity researchers have demonstrated that divergent and convergent thinking are both present and required creativity: "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" [34]. Indeed, creative processes often unfold as transitions between the two modes, "cycling repeatedly through a process of divergent and convergent thinking" [42], and in Perkins' studies of inventiveness, it is demonstrated that inventive people are often "mode shifters" [33]. This mode-shifting further emphasized the non-linear nature of the design process.

For the purposes of our study in this paper, the main point is that while divergent and convergent thinking are distinct and different modes of thinking, they are both required in creative problem-solving processes. If we wish to understand the role that analog and digital tools play in design processes, we should therefore inquire into if and how they influence divergent and convergent thinking, not just on the macro-level of an entire design project, but also on the micro-level of individual design sessions.

3 METHOD: USING LINKOGRAPHY TO UNFOLD THE DESIGN PROCESS

3.1 Experiment design

The data was collected using a randomized controlled experiment with a repeated measure. No strong hypothesis was formulated at the outset of the study; rather, we explored a range of possible manifested variables that – following conceptual and empirical literature on linkography – were expected to reflect situations of divergent and convergent thinking: critical moves, unidirectional moves, and orphan moves (for more details explanation, see section 3.7 below). Such exploratory experimental designs are intended to establish initial relationships in contexts where it is unclear whether they exist and/or which characteristics might be impacted [11]. As such, they precede narrow hypothesis testing.

3.2 Participants

Thirty designers participated in the study, in groups of three. Participants were recruited via email, presentation in groups for UX professionals and by personal reference, and as a minimum requirement, each participant needed to have completed at least one HCI or interaction design course at university level, have completed at least two design projects (median = 8), and have collaborated previously with the other two group members. We offered 15EUR/18USD p/h as compensation. Two groups were excluded from the data; one group was erroneously given the same task for both conditions, and another had a member drop-out for the second condition.

The participants reported their familiarity with tablets, stylus, large interactive displays (LIDs) and real-time collaborative software (RCS) on a Likert type scale where "never"=1, "very rarely"=2, "once or twice a month"=3, "every week"=4, "every day"=5 and "several times a day"=6.

	Tablet	Stylus	LID	RCS
Mean	2.926	1.704	2.000	4.370
Median	3.00	1.00	2.00	4.00
Std. Deviation	1.47	1.07	0.795	0.74
Minimum	1.00	1.00	1.00	3.00
Maximum	6.00	5.00	4.00	6.00

Table 1: Familiarity with devices and tools

As illustrated in table 1, all participants were frequent users of RCS like Google Docs, while more diverging, tablet-use was also relatively common amongst the participants. On the other hand, the participants were not used to using a stylus or LIDs. This pattern was highly expected based on the general (lack of) pervasiveness of LIDs and our knowledge about design agencies' current use of tools stemming from the collaborative design proces, which informed the development of our tool.

3.3 Procedure

The groups were asked to complete two different, but comparable, design tasks using either analog tools (sticky notes, pen and paper, whiteboard) or digital tools (the Cards and Boards system). In order to achieve a balanced design with an equal amount of groups in all possible combinations (as indicated in table 2), participant groups would complete the first task in either the digital or analog condition, and the second task in the opposite condition. The order of these conditions were randomly assigned. The design tasks were based on those used in Jensen et al.'s experimental study on the use of digital and physical sticky notes [26]. One design task asked the participants to develop a new online service for the delivery of milk and cookies, and the other to develop a smart wardrobe. In order to mitigate fatigue and potential ordering effects, the experiments were conducted with around a week in between, with some variation due to a few reschedules (M=7.5, SD=3.9).

In the days before taking part in the trial that contained the digital tool, the participant were asked to engage with learning materials about the tool in the form of video tutorials. The designers were required to pass a multiple choice test (10 out of 10 correct answers), to confirm that they had engaged with the material and were familiar with the functionality and features of the tool. The designers that failed the test were prompted to return to the material or consult with the experimenter. All participants passed the multiple choice test within the first or second try, without contacting the experimenter.

	First trial	Second trial
Group 1	Analog+Task1	Training→Digital+Task2
Group 2	Analog+Task1	Training→Digital+Task2
Group 3	Analog+Task2	Training→Digital+Task1
Group 4	Analog+Task2	Training→Digital+Task1
Group 5	Training→Digital+Task1	Analog+Task2
Group 6	Training→Digital+Task1	Analog+Task2
Group 7	Training→Digtal+Task2	Analog+Task1
Group 8	Training→Digital+Task2	Analog+Task1

Table 2: Groups of participants were randomly assigned to both condition and task. This table is represented as sorted for ease of reading.

The experiments lasted 60 minutes, with 45 minutes of actual 'design time', and the remaining 15 minutes for practicalities such as welcoming the participants, setting up devices, answering participant questions, and any critical feedback about the experiment that could have invalidated the results. During the design task, the designers worked completely autonomously, execept for at the 40 minute mark, where the experimenter would signal they had five minutes left.

Video and audio from the session were captured from two different angles. The materials produced by the designer in the analog condition were photographed with a high-res camera and the digital boards were downloaded and saved in the digital version. The screen of the digital board was recorded in real-time to ease the coding of the video, and the webstrates [29] platform allows for highly detailed, sequential inspections of every single changes made in the application (strokes, keypress, movement, etc). A total of around 36 hours of video material was collected in the study in addition to photos and scans of the analog sketches and sticky notes.

Figure 3: Example of three concurrent video-streams

3.4 The analog experimental condition: whiteboards, markers, and sticky notes

In one experimental study condition, study participants exclusively made use of analog tools in the form of whiteboards, markers, and sticky notes. This setup is similar to how many designers currently carry out collaborative design ideation sessions. To clarify the similarities and differences between this condition and the digital experimental condition, participants here had access to two whiteboard (approx. 1.2 x 2 meters) and ample supplies of sticky notes and markers of different colors. We may take the constraints and affordances [16] of sticky notes for granted, but as examined in [3], they have properties that lend themselves well to supporting collaborative creativity: they are lightweight and can be spread out in a room, repositioned, and affixed to surfaces; they invite free form annotation; they are well-known and do not require any training of users; they are ubiquitous and cheap; they are often perceived to be a temporary and ephemeral medium suitable for conceptual work such as ideation; and they are versatile and can be used in a large number of domains: "(...) visual domains may use them for sketching; functional domains may use them to make models; and conceptual domains may use them to relate text and concepts" [3]. Moreover, they render co-present actors' actions visible, which can be highly beneficial in face-to-face synchronous shared-space creative collaboration.

3.5 The digital experimental condition: the Cards and Boards system

Cards and Boards [8] is collaborative, digital remediation of analog sticky notes and whiteboards. It is built on the Webstrates platform [29] and thus supports real-time collaboration via any device that runs a browser, although the interface has here been explicitly designed to function on touch screen devices from tablet size and up to large touch-enabled displays with stylus input as well as laptops. In the experiments reported here, the devices in use were two 12.9"

iPad Pros with stylus and wireless keyboards as input devices, one 55" Microsoft Surface Hubs, also with stylus and wireless keyboard input, and the designers individual personal or work laptops. Cards and Boards can be used on these devices interchangeably and in combination with full support for real-time collaboration.

Cards and Boards is designed to function as an alternative to the use of physical sticky notes, whiteboards, and flip charts in design. It is built around the notion of boards, which are large, zoomable canvases onto which users can add and manipulate free-hand stylus input and cards. Cards are equivalent to sticky notes and are thus smaller containers of content, which can be either free-hand stylus input such as sketches or scribbles, text input via keyboards, images, videos, markup or links, which imports an image to the cards via the Open Graph protocol [23]. Moreover, users can create boards within boards. Since the system builds on the Webstrates platform, each board has a unique URL, and changes to the content of a board are synchronized in real-time to other users of the same board.

Cards can be edited, copied, pasted, deleted, and moved on the board individually or grouped in a selection of cards, and they can be copied and pasted. Moreover, users can change the color of cards individually or as part of a grouped selection. Users can navigate on the board using pan and zoom, supplemented by a mini-map in the top right corner, which shows the current view. Users can open two boards side by side via a split-screen functionality. In this split-screen mode, users can copy and drag-and-drop content between boards.

3.6 Similarities and differences between the analog and digital experimental conditions

While Cards and Boards is a digital setup, it is designed to tap into designers' current use of analog cards and boards in their work processes. The development of the system is based on in-depth observations and participatory design sessions with professional designers in order to fit in with existing work practice, and it has been refined through several iterations and deployed and tested in both controlled studies and longitudinal, real-life design projects. We emphasize this to indicate that while it is not a commercial off-the-shelf product, we expect that findings from studies will not be invalidated by basic usability problems or lack of fit with the domain of use.

For the purposes of the study presented here, Cards and Boards offers digital counterparts to the analog tools in use, ie. sticky notes, pen, and boards, which function in similar ways, i.e. digital pen strokes can be erased and cards can be moved and placed on top of other cards, and input from multiple users is simultaneously updated on all devices. Moreover, the system provides additional features: The boards are infinitely zoomable and have a mini-map to support overview and navigation; they can contain a much larger quantity of content that analog boards; and boards can be nested within boards to support overview and organization of content. Together with e.g. the ability to have machine-written, image, or link-cards, these features allow for a potentially higher level of information-density. Cards can be duplicated, and users can select, move, and change the color of multiple cards in a group. Card content can be easily edited, and it can contain multimedia content. Moreover, content is persistent and can be viewed in split-screen modes, meaning that designers can e.g. navigate instantly back and forth between boards to compare and transfer content between them.

Of importance for this study, the system also stands out from the analog counterpart in that multiple users can access boards via different devices, e.g. two users can work on a board on a Surface Hub, while a third user adds and manipulates content on the same board via an iPad. In contrast, analog tools have qualities that are not replicated in the system. Whereas the digital sticky notes only reside on boards, analog sticky notes can be moved and manipulated in the entire room, and the location of the analog boards and the content on them is fixed in space. This may seem like an obvious statement, but it could potentially have consequences for how design processes unfold, for instance regarding how users of analog boards all have the same spatial understanding of where board and the content on it is placed when they refer to it in their joint discussions.

3.7 Linkographic analysis

Linkography is a method to meticulously assess the design process or productivity, and it was introduces in 1990 by Goldschmidt [17]. It leverages protocol analysis' [10] by leveraging detailed account of verbal reports as the empirical foundation [18]. The method involves parsing the transcribed and segmented protocols into small units which are referred to as *design moves* which are then *linked* to each other in order to create the *linkograph*. By doing so, the associations of each individual design move can then be traces, and the overall session can be probed for patterns or properties related to e.g. the proportion of linking or new moves.

A design move is defined by Goldschmidt as "a step, an act, an operation, that transforms the design situation somewhat relative to the state it was in before[...]" and "[...] akin to its meaning in chess [...]"[18]. An average move is argued to be around 7 seconds in duration. Goldschmidt is emphasized that this type of design move differs significantly from e.g. the use of 'moves' by Shön [18]. When parsing a protocol from teamwork into moves, turn taking is suggested as a common principle, but it other breakdowns like sentences are also proposes [18].

A moves is not a stand-alone entity, as they are not generated in isolation from previous moves. To address this, links between moves are established in order to advance the analysis. Goldschmidt states that links among moves can be determined: "[...] based on the contents of moves. Deciding whether two moves are linked is done by using common sense under the condition of good acquintance with the discipline and with the design episode in question" [18]. The question of whether there is a link or not is asked systematically for all moves in the parsed protocol, yielding $n(n-1)2$ number of links where n is the total number of moves [18].

Links between moves can only be establish in retrospection, or in other words, when conducting the analysis all we can look for is what Goldschmidt refers to as *backlinks* [18]. By examining a single move, we can look at the moves that came before it, to establish whether there is a link or not. However, once this link has been established, the link serves both as a *forelink* and a *backlink* depending on where it is linking from and to. In this way, the link between move 2 and move 3 is, at the same time, the forelink for move 2, and the backlink for move 3. A move is naturally able to

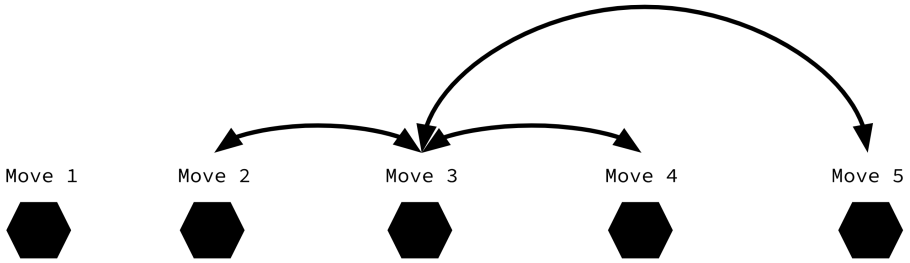

Figure 4: Moves and links between moves

have several links, e.g. if. move 3 links to both back to move 2 but also forward to move 4 and move 5.

Linkography opens the door to an array of potentially interesting factors and elements regarding design cognition and the design process. In this paper, we focus specifically on a handful of factors, which we will briefly introduce. For at full set of the available variables and factors we refer to Goldschmidts book devoted to this method [18].

3.7.1 Orphan Moves. are moves with that are not linked to other moves. Goldschmidt suggests that they may be frequently observed when dealing with less experienced designers [18]. An examples is in the early phases from group 7, analog condition:

> Move 11 (Mary Jane): I do not really know if it is an idea and I do not know if we can incorporate it but.. That one Jim Carrey movie where he is a news host and says 'and that's how the cookie crumbles'.. If we could somehow incorporate some humor element into it..

The idea of incorporating the quote from the movie Bruce the Almighty immediately brings out the laughter in the group, but is not in any way incorporated, returned to, or dealt with further in the session.

3.7.2 Critical Moves. are the moves that generates the most links to other moves, and thus the most 'influential' in the linkograph. Their critically is attributed to the direction using a threshold, which can vary from study to study, but should be set so that it yields approx. 10-12% of all moves as critical [18]. An example from our data-set is from group 6, digital condition:

In this snippet the inclusion of AR as a feature is proposed by Nick in move 18. It does not rest on, or is in any way related to previous moves, but inspired several moves in the remaining part of this session, which owns it the status of critical forelink move or *CM>*. Likewise, move 23 also plays a significant part in this protocol, when Kevin proposes that the some sort of framing or "holster" is needed, by recognizing and relating to two previous moves 18 and 21. Had it not been for the two forelinks continuing far out in the future of the protocol move 23 would have been designated citical backlink move or *<CM*, but because it both links backward and forward an equal amount above the threshold it is actually a critical move in both directions *<CM>*, which are relatively rare [18].

Critical moves due to forelinks and and backlinks are proposed to be reflective of divergent and convergent thinking in the context of Linkography [18, 19]. Forelinks manifest divergent thinking as they are representatives of "[...] steps forward, the consideration of more options and possible solutions, further development." [19], whereas backlinks manifest convergent thinking by representing "[...] appraisal, evaluation and confirmation" [19]. It is also clear from the example above, that move 18 present a novel *exploration in a different direction* as in the wording by [12]. By empirically examining the relationship between <CMs and CMs> we are able to obtain a measure of the divergent and convergent thinking that goes on at the cognitive scale. This approach has previously been used to study divergent and convergent thinking aspects in designers with different expertise [19] and to contrast design methods [22]. A recent review of the empiciral understanding of the conceptual constructs of diveregent and convergent creativity, the authors suggested that the linkographic approach is a promising development towards using the goal of using "[...] the same criteria to measure both divergent and convergent thinking" [4].

3.7.3 Unidirectional moves. are moves that do not link to previous moves, but is linked or referred to by following moves. Goldschmidt states that unidirectional moves "[...] suggest that at the instant of their generation the designer was concentrating either on what had transpired up to that point (in the case of backlinks only), or on new thoughts that left behind what had been done thus far[...]" [18].

3.7.4 Link Index. is plainly the the average amount of links per moves. This can vary from the hypothetical end-points of 0 to n(n – 1)/2, although highly unlike to be even close to these. Goldschmidt states, that the Link Index "[...] hints at the designer's effort to achieve a synthesis" [18]. But similarly warns of about treating a high link index as a sign of good or creative design per se. Finally, it is suggested that link index may vary dramatically within a session [18].

4 RESULTS

The data corpus of protocols consist of 3941 segments, or 58.721 words, or 117 pages in 12-point Times New Roman. Broken down per group and per condition, this averaged to 246 segments, or 3.670 words. Roughly every third segment in the protocol was coded as a move, totalling 1239 moves, or 77 moves per session. 12.75% of moves were counted as critical (i.e., with at least two links in either direction), which is close to the recommended 10-12% [18]. For all of these measures – number of segments, words, moves, and critical moves – there was no significant difference between the analog and digital conditions. We conducted an initial

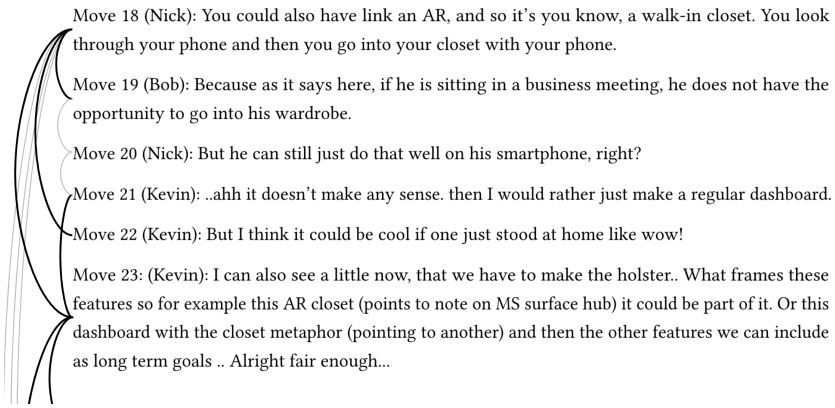

Figure 5: Illustrated snippet from parsed protocol

IRR where all four authors independently coded the same group using only Goldschmidt's book [19], resulting in a Fleiss kappa of .45 ("moderate agreement"). Following this, all coders discussed their understanding of the method before coding the rest of the corpus. We consider the .45 to be the baseline and that the IRR for the remaining corpus to be higher, as a results of the discussion.

We found that the use of digital tools in a design task had a large effect on three measures: **backlinking critical moves**, **orphan moves** and **link index**. We will present the results relating to each of these measures individually and examine how they affect the rate of convergent and divergent thinking by the participants. Then, we will discuss how these measures relate to each other, as well as other measures that were impacted by the digital tool to a lesser degree.

4.1 Backlinking Critical Moves

Backlinking critical moves are utterances which refer to at least two previously discussed moves, for example by using them to compare or evaluate the current state. Figure 6 shows an example of a backlinking critical move, performed by Group 7 in the digital condition:

Move 49 in figure 6 shows how James performs a critical move by referring back to three previously discussed ideas and their similarities. Using these ideas, he makes a design move of his own by categorising them as "personalize", thus converging on a more narrow design compared to the previous state.

Our analysis suggests that the use of digital tools strongly impacts the prevalence of backlinking critical moves. In the digital condition, they comprised 7,2% of all moves (M=.072, SD=.022), compared to only 2,6% when using the analog tools (M=.026, SD=.023). Linkographic analyses relate the occurrence of backlinking critical moves with the presence of convergent thinking, thus our results suggest that digital better support convergent thinking styles in design processes.

4.2 Orphan moves

Orphan moves signify that the proposed step in the design process (e.g. a new idea or change of direction) did not impact future design movies. Figure 8 shows a linkographic notation of orphan moves from the beginning of a session.

There are a variety of reasons why a move was left unlinked. Most of the groups started their design session by brainstorming and putting many ideas on the table (metaphorically and literally). In these dynamics, moves might not be returned to because they were explicitly deemed irrelevant, conceptually too far from the topic, or buried by more salient alternatives. In some conditions, a designer in the group decided to propose new ideas, features, or changes at the very end of the session, leaving insufficient time to incorporate these moves. In addition to these temporal reasons, a few orphan moves were created because of logistical problems, for example, if the idea was illegible because of poor handwriting, described too briefly to be interpretable at a later stage, or removed to make space for other artefacts.

The proportion of orphan moves in a design session reflects to what extent previous ideas are appreciated, dealt with, or related to in moves later on in the process. Fewer orphans means that, generally speaking, the final design was the result of a comprehensive convergence of all or most divergent ideas proposed. Our analysis shows that the use of digital tools strongly decreased the proportion of orphan moves, with just 14% of all moves representing orphan moves (M=0.14, SD=0.11), compared to 23% in the analog condition (M=0.23, SD=0.15).

4.3 Link index

We observed a difference in link index, with the digital condition resulting in a higher number of links per move (M=.75, SD=.10) compared to the analog condition (M=.57, SD=.16). In other words, the same designers, working on similar tasks, were more inclined to e.g. ensure that a new move could be evaluated as appropriate and consistent with previous moves, or that the steps taken build on or challenge the previous steps.

While we can only speculate about which characteristics of the digital lends it self to more linking, inspection of the video materials provides us with a couple of interesting insights. The first is the possibility for easily doing re-groupings, re-coloring and effortless sorting, like in the case yellow highlight in the middle, where three notes are group physically, but while at the same time being obvious

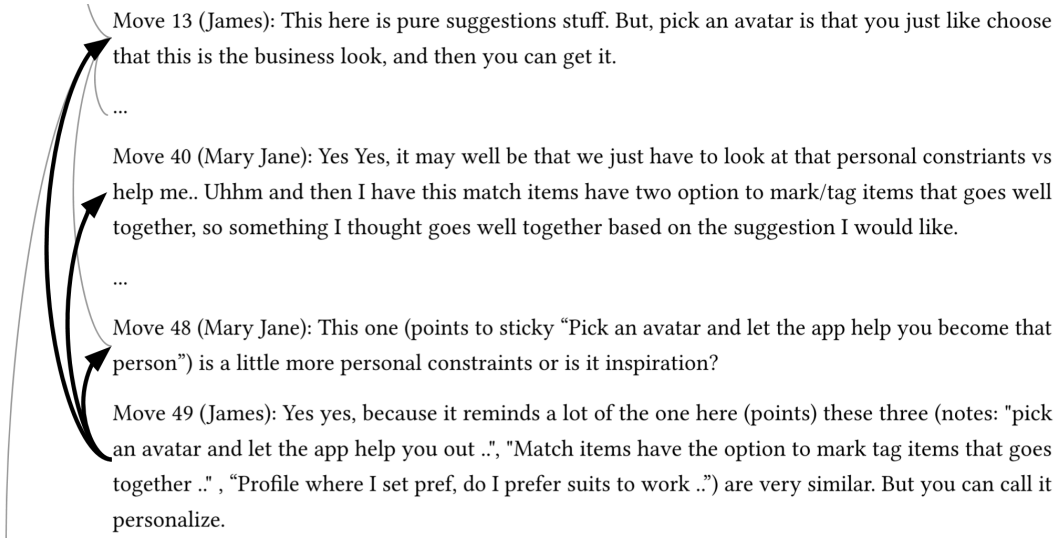

Figure 6: Illustrated snippet from parsed protocol showing a clear critical move due to backlinking

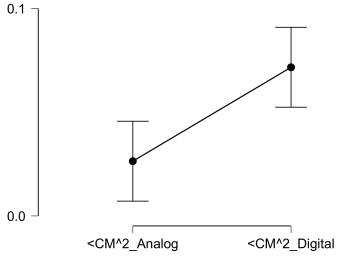

Figure 7: Descriptive plots of comparisons between analog and digital for <CM 95% CIs

that green note originally belonged to another group. Secondly, and as is exemplified by the note highlighted in the lower right corner, more notes are readable at the same time and more text can be fitted on a note while maintaining readability. Additional characteristics of the digital may be considered, albeit with an emphasis on the speculative nature of this, as no causality can be drawn from an individual feature in a rather complex system like the one used in this study.

On a more general level, this increase in linking index can be understood as a sign of convergent thinking in its effect of 'combining what "belongs" together' as put by Cropley [6]. In other words, higher Link Index means more effort is being put into relating to the existing, and thus ensuring that moves are congruent with existing moves, which is potentially a sign of convergent thinking. However, we also emphasize that such a claim may in fact have been made in the opposite direction, by following the logic that low levels of interlinking only involves combining what is immediately perceived as similar, whereas high levels of interlinking would require a combination of the disparate (which would in turn err on the more divergent side of the spectrum).

4.4 Factors not affected

In terms of forward-linking critical moves we observed no clear difference between analog (M=.071, SD=.050) and digital (M=.080, SD=.028), which would, as previously mentioned, have been an indicate of more or less divergent thinking. Another measure proposed in the Linkographic method is concerned with moves that are *unidirectional*, that is, they only links in one direction. Goldschmidt states that the proportion of these unidirectional moves (UDIR) in any direction (< or >) potentially informs us about the nature of work done, or may be related to the experience of the designers. However, no clear difference was observed across conditions in neither directions, see table 3.

All the variables yielded insignificant Shapiro-Wilks (in the same order as table 3: p=.26;.08;.63;.24;.42;.10), and thus we considered the assumption about statistical normality to be met.

4.5 From theoretical concepts to manifested measures of convergent thinking

Divergent and convergent thinking are conceptual constructs that are not directly measurable, and back-linking critical move has previously been employed as an indicator of convergent thinking [19]. Continuing this line of thought we further proposed that Link Index and Orphan Moves can be considered relevant manifested variables for the conceptual concept of convergent thinking. Eventually, the two may be naturally related in various ways. While it is possible to have an increase in Link Index without a decrease in Orphan Moves, e.g. by only linking moves that are already connected to other moves instead of linking them to unlinked moves, this would probably rarely be the case, and an increase in the general linking in the protocol is potentially accompanied by less Orphan Moves and vice versa.

By looking solely on the difference in backlinking critical moves, the findings are interpretable as an indication of more convergent

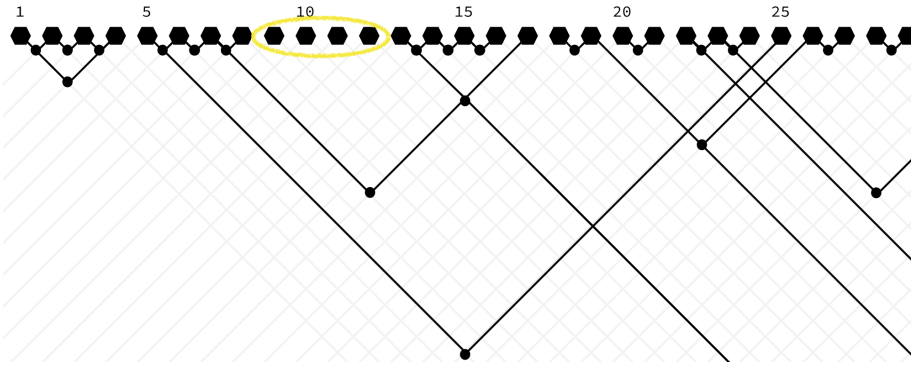

Figure 8: Orphan moves from the beginning of the session, highlighted with yellow circle

Table 3: Paired Samples T-Test

							95% CI for Mean Difference		
		t	df	p	Mean Difference	SE Difference	Lower	Upper	Cohen's d
Link index	-	-3.904	7	0.006	-0.177	0.045	-0.285	-0.070	-1.380
CM>	-	-0.581	7	0.579	-0.009	0.016	-0.046	0.028	-0.206
<CM	-	-3.931	7	0.006	-0.045	0.012	-0.072	-0.018	-1.390
UDIR>	-	-0.312	7	0.764	-0.005	0.015	-0.041	0.031	-0.110
<UDIR	-	1.247	7	0.253	0.030	0.024	-0.027	0.087	0.441
Orphan	-	4.036	7	0.005	0.083	0.021	0.035	0.132	1.427

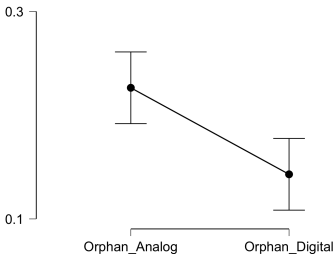

Figure 9: Descriptive plots of comparisons between analog and digital for Orphan Moves 95% CIs

thinking in the digital conditions compared to the analog, considering that this factor is already established as a manifested measure for convergent thinking [18, 22]. However, we also propose that higher levels of link indexing and a decrease in orphan moves can be appropriately interpreted in the same manner.

4.6 Discussion

We are hesitant in proposing strong implications for design practice or the development of novel tools due to the nature of the experiment, in which we focused on a very particular aspect, namely divergent versus convergent thinking in a contrived setting. In regards to the finding that the digital setup leads to more convergent thinking, we believe that this can be an important i consideration for designers when they select tools to support design activities. There may be phases in a design process in which convergence is more desirable than divergence, and vice versa. For instance, if many ideas have already been developed in the early stages of a design process, a design team might want to select tools for their next session that would make them more likely to move towards convergence, such as the Cards and Boards system presented here. In contrast, if a design team wishes to broadly explore the space of opportunities in a project, they might want to opt for an analog setup. This echoes Dalsgaard's [7] proposition that design tools - for better or worse - steer designers towards specific types of outcomes. As a consequence, an important aspect of design competence is to understand how and why specific tools frame and constrain the design process and its outcome.

A pertinent question is why the digital setup is more conducive to convergent thinking. Our analysis does not provide conclusive answers to this, and it would be necessary to carry out further studies isolating the specific mechanisms of the digital to examine this. If we were to speculate, one potential answer could be the information density and overview that participants have access to in the digital setup. Since the system offers an overview of a large number of notes, and each note on average contains more information than can be comfortably be handwritten on a paper sticky note, participants are exposed to more prior ideas on which they can build, or which can serve as sparks for related ideas. Moreover, this space is still visible when participants enter content into new notes. In contrast, when using paper sticky notes, participants move their focus from the board to a new, empty note when they create new ideas. To reiterate, these are speculations, since our mode of analysis here is not apt for answering this question, but it is one that would be relevant to examine in future work.

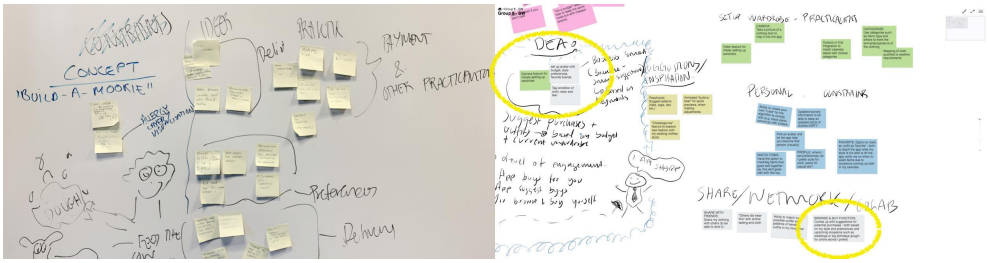

Figure 10: The final whiteboard in the analog condition, and a screenshot of the final canvas in the digital condition of the same group

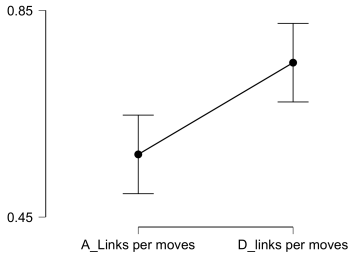

Figure 11: Descriptive plots of comparisons between analog and digital for Link Index 95% CIs

However, we must also note that divergent and convergent thinking are just two out of many aspects to consider for designers in practice. For instance, if a design session involves participants with no prior knowledge of the digital system, the analog tools may be the better choice because they can be immediately understood and used. On the other hand, systems such as Cards and Boards system may be a better choice than analog setups in projects that span several design sessions because it provides shared digital spaces in which content is persistent, accessible, and customizable, enabling participants to continue working on them throughout a project, both when they are physically co-present and when the work remotely [9]

5 CONCLUSION

We compared classic analog design tools with a digital tool designed to support current design practices to explore how **the digital tool potentially leads to an increase in convergent thinking in the design ideation process**. Based on protocol analysis and the method of linkography, we discovered an increase in the prevalence of **back-linking critical moves** together with a decrease in **orphans moves** and a higher level of **link indexing**, which we - in line with Goldschmidt [18] - interpret as indicators of convergent thinking. Moreover, we also find that the two setups otherwise performed similarly. The latter is worth mentioning since it suggests that the digital setup can be a feasible alternative to the analog one, even though designers in practice appear to demonstrate a preference for the analog setup for ideation [32].

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