THE IMPACT OF WORKING MEMORY LIMITATIONS ON THE DESIGN PROCESS DURING CONCEPTUALIZATION

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Abstract. This paper presents the cognitive activity differences of six expert architects when they design in blindfolded (BF) and sketching (SK) conditions. It was observed that all participants' overall cognitive activity and perceptual activity in the BF sessions dropped below their activity in the SK sessions, approximately after 20 minutes during the timeline of their design activity. This drop in performance can be explained by higher cognitive demands under BF conditions. In the absence of sketching, architects may experience an overload of visuo-spatial working memory (VSWM). We also tested whether this may have an impact on the linking of their design ideas. We previously reported that the intensity and the information content (entropy) of the idea development were not influenced by VSWM load. The reach of idea links was found to be smaller in the second half of the BF design sessions. Working memory limitations had an impact only on the reach of idea links. We discuss whether these differences are dependent on working memory limitations or idea saturation during conceptual designing.

Keywords: Conceptual design, working memory, idea development, protocol analysis

Design cognition studies have emphasized that mental images are externalized through the act of sketching (Ullman et al. 1990, Goldschmidt 1995, Kokotovich and Purcell 2001, Kavakli and Gero 2001), although it is uncertain "how and when" mental imagery processes might be interacting with sketching activity. This is a key question for researchers interested in visual and spatial reasoning in design; however the number of design related studies is relatively small. The main reason is that it is a challenge to develop appropriate study methods for investigating mental representations and their interaction with external representations. In this paper we explore whether imagery processes have to be supported by the act of sketching during conceptual designing. The answer "yes" is almost common sense for design researchers and cognitive scientists, because there is considerable evidence that externalization acts as an external memory. For example, when someone is told a telephone number once and then asked

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to remember it, this could be a challenge for him/her without putting the number down on paper. The capacity of short-term memory (STM) is limited and may impede the solving of complex problems which require higher cognitive processing performance . Long-term memory (LTM) may be a substitute workspace with its large capacity; however it may not allow rapid retrieval and storage of information. External memory, such as sketches, notes, and diagrams is considered a key for the problem solver to overcome limitations of STM and LTM.

We start our argument with Miller's (1956) statement that the "human short-term memory is limited in the amount of information it can simultaneously hold and the number of mental operations that can apply to that information". In Miller's view STM was a single component and its volume was seven plus minus two. This view was replaced by a multi-component theory of STM, called the working memory (Baddeley 1986, 2000) and the estimates of the capacity have been reduced (Cowan 2001). Research on working memory examined its connection to the long-term memory and how information is stored, represented, and accessed. The working memory model is followed by the theory of long-term working memory (LT-WM) which proposes that an expert's memory consists of memory chunks that were grouped together (Ericsson and Kintsch 1995). The experts acquire a domain-specific skill and knowledge through training where they learn how to use their knowledge strategically (Ericsson and Smith 1991, Kvan and Candy, 2000). Kavakli and Gero (2003) explained experts' higher levels of cognitive processing by showing that an expert architect's cognitive chunks were structured in a way that they stayed within the limits of Miller's magic number 7 (+/- 2), whereas novice's chunks exceeded this limit. In addition to the chunking theory, skilled imagery theory provides a comprehensive explanation for experts' extraordinary performance (Ericsson and Kintsch 1995, Saarilouma 1998).

1. Background

In design research, sketching as an external representation is considered as the medium to set out thoughts on the fly, that is to generate design ideas, design concepts and further develop and elaborate them. One of the most important roles of external representations in design contexts is to facilitate new ideas and design concepts (Goel 1995, Goldschmidt 1991, Laseau 1989, Do et al. 2001, Suwa and Tversky 1997, Purcell and Gero 1998). During the early phases of conceptual designing, a designer may start with one idea/concept and then develop this into another, while keeping track of how his/her ideas have evolved by drawing them on paper. Design studies found that sketches store the ideas and make them accessible (Akin 1986). Easier access to earlier design ideas is likely to stimulate increased use of them. Sketches can facilitate the re-use of information in previously generated design ideas and also can facilitate more links between ideas during the design activity.

For many expert designers, sketching is the medium for developing ideas because they have been trained to do this. Design ideas and the representations are specific to the individuals creating them. This means that the designer generates and organizes each line and notation in a way that has specific meaning to her/him compared to what someone else can read into them. These depictions in a sketch can be ambiguous such that when the designer looks at them later during his activity, they have a high potential for retrieving the previous information as well as triggering re-interpretation (Purcell and Gero 1998). In design research, re-interpretation of drawings is associated with how the elements constituting a depiction are organized within the whole, so that it could take on a different (new) meaning. Similarly, mental imagery experiments have emphasized the role and necessity of externalizations for mental synthesis of parts/objects as well as for re-interpretation (Chambers and Reisberg 1985, Anderson and Helstrup 1993, Verstijnen 1998, Kavakli et al. 1998, Kokotovich and Purcell 2000). These studies provide evidence that re-organization, maintenance, transformation and inspection of images/shapes would be more difficult for designers if they were not externalized. It can be concluded that the externalizations support the imagery processes.

Scaife and Rogers (1996) used the term computational off-loading in a general way to describe how certain kinds of external information can reduce the mental effort involved in achieving a task. Similarly Zhang (1996) argued that tasks involving perceptual judgments can be less demanding than those involving mental arithmetic. In another study Zhang (1997) attempted to provide a more substantial model for the analysis of distributed problem solving. One of the key conclusions from Zhang's (1997) work is that appropriate external representations can reduce the difficulty of a task by supporting recognition-based memory or perceptual judgments rather than recall. This conclusion parallels the findings on mental synthesis and re-interpretation in design studies.

1.1. SKETCHING AND BLINDFOLDED DESIGNING

The role of imagery in architectural design has been emphasized only anecdotally. Examples are often quoted of major architects, such as Frank Lloyd Wright, who could conceive of, and develop a design, entirely using imagery with an external representation of the design only being produced at the end of the process (Toker 2003).

Designers use their mental imagery both when they sketch and when they do not sketch, and in both cases mental representations are essential in designing. The use of imagery in designing has been emphasised in how designers draw figures, perceive figures, modify and re-interpret them; however it has not been widely accepted as a cognitive tool for designing. Athavankar (1997) questioned whether the use of imagery alone can be a tool for designing. His experimental study resulted in claims that it was possible for an expert designer to develop a product design using his imagery only. Similar findings were reported in a study with expert software designers (Petre and Blackwell 1999) where they were required to design using their mental imagery only. The results indicated some common cognitive mechanisms and strategies informing the use of imagery alone while designing.

Bilda et al. (2006) examined expert architects' design activity when they were blindfolded and when they were sketching and investigated the outcomes from these activities. The design solutions from sketching and blindfolded sessions were assessed by judges and the outcome scores showed no significant difference. Expert architects were able to produce solutions that were as good as sketching outcomes by relying on their memory. The study suggested that sketching might not be the only way to design conceptually for expert architects.

If designers are able to design blindfolded, then why do they prefer to sketch? The answer may be that sketching makes thinking easier; by "seeing it" and "storing it". Sketching may help to reduce the load on the cognitive processes needed to design. Following from the results of the three architects' reported in Bilda et al (2006), this paper examines the cognitive activity and idea development of six expert architects when they were sketching and when they were blindfolded.

1.2. VISUO-SPATIAL WORKING MEMORY LIMITATIONS

Imagery has been claimed to be the visuo-spatial sketchpad (VSSP) of the mind in the model of working memory (Baddeley 1986; Logie 1995). The VSSP is hypothesized to produce internal representations and process visual or spatial material therefore it is considered to be an alternative imagery model. In the recent version of the working memory model, four components are hypothesized to process different types of information: the phonological loop, the visuo-spatial sketchpad, central executive and an episodic buffer. In this model the visuo-spatial sketch pad is likely to be related to visual perception and action while the central executive is related to attention, control of action and planning (Baddeley 2000). The episodic buffers are coupled to a common central executive and to corresponding long-term stores (Baddeley 2003). The role of working memory in design has been as a workspace for cognitive processes that retains information in visuo-spatial and/or verbal modes. The workspace is hypothesized to provide coordination of visual, spatial and verbal information and retrieval from long term memory with the episodic buffer and central executive.

Research in visuo-spatial working memory claims that maintaining and transforming visuo-spatial information demands central executive resources, in other words requires mental effort (Baddeley 1986; Logie 1995). Based on empirical evidence, imagery activity intensively uses up working memory resources and the capacity of the VSWM is limited when visuo-spatial tasks are done using imagery only (Ballard et al. 1995; Walker et al. 1993; Phillips and Christie 1997). The theory suggests that externalization of visuo-spatial information is needed to free up the working memory so that the other tasks can be carried out effectively. For this reason drawings and diagrams play an important role in designing.

2. Hypotheses

The review of the VSWM research suggests that the use of imagery alone in design for extended periods of time would exhaust central executive resources. This means that the processing of visual and spatial information would be more difficult as the design activity progresses. Cognitive load will be accumulated over time when the designers are not allowed to externalize and this might cause their performance to drop over time. This may have an impact on linking their design ideas or their performance in linking concepts and ideas. In contrast, continuous externalization off-loads the VSWM, so that other tasks can be done effectively.

We have developed four hypotheses that test the cognitive effects of sketching.
Hypothesis 1: Rate of cognitive activity will decrease noticeably after a certain amount of time if sketching is not allowed during conceptual designing.
Hypothesis 2: Idea generation slows along the timeline of the design activity when designers are not allowed to sketch.
Hypothesis 3: Designers can remember and keep track of their ideas better when they are able to sketch compared to when they are not.
Hypothesis 4: Short- term memory limitations have an impact on the reach of idea links.

3. The Experiment

The six architects who participated in this case study (2 female and 4 male) have each been practicing for more than 15 years. Architects A1 and A2 have been awarded prizes for their designs in Australia;

they have been running their own offices and also teaching part-time at the University of Sydney. Architect A3 is a senior designer in a well-known architectural firm and has been teaching part-time at the University of Technology, Sydney. A4 works for one of the Australia's largest architectural companies and has been the leader of many residential building projects from small to large scales. A5 is one of the founders and director of an award wining architectural company. A6 is a famous residential architect in Sydney, and directs his company known by his name with 50 employees.

3.1. DESIGN OF THE EXPERIMENTS

The first group of three architects was initially engaged in a design process where they are not allowed to sketch. In this condition we used a similar approach to that taken by Athavankar (1997): we had the designers engage in the design process while wearing a blindfold. This phase is called the blindfolded (BF) condition where they receive design brief 01. Design brief 01 requires designing a house for two artists: a painter and a dancer. The house is to have two studios, an observatory, a sculpture garden and living, eating, sleeping areas. At least a month after the BF condition the same three architects were engaged in a design process where they were allowed to sketch. This phase is called the sketching (SK) condition where they receive design brief 02. Design brief 02 requires designing a house on the same site as design brief 01 this time for a couple with 5 children aged from 3 to 17, that would accommodate children and parent sleeping areas, family space, study, guest house, eating and outdoor playing spaces.

The second group of the three architects was initially engaged in the SK session, where they received design brief 02. Then after one month they were engaged in the BF session (where they are not allowed to sketch) and were required to work on design brief 01. The procedures for conducting the experiments are explained and discussed in Bilda et al. (2006).

3.2. ANALYSIS OF COGNITIVE ACTIVITY

The protocols from both SK and BF sessions were segmented using the same approach as for segmenting sketching protocols i.e. by inspecting designer's intentions (Suwa and Tversky 1997, Suwa et al. 1998). The imagery and sketching coding schemes used the action categories from a coding scheme developed by Suwa et al. (1998).

The imagery coding scheme consists of six action categories: visuo-spatial actions, perceptual actions, functional actions, conceptual actions, evaluative actions and recall actions. The sketching coding scheme consists of drawing actions which are specific to the sketching activity. In this paper our focus is not on the drawing actions but on action categories which are common to both conditions. We selectively used actions from perceptual, functional, and conceptual action categories in the Suwa et al. (1998) coding scheme. These common action categories are presented in the Appendix.

Each architect's BF and SK sessions were coded with the related coding scheme. The coding phase included a first run, a second run and finally an arbitration phase where codes are selected and accepted from first or second run coding. The complete audio/video protocol for each session was coded twice by the same coder. In order to avoid the repetition of the same view the analyst had a break of a minimum of one month period between the two coding passes. When the two runs were completed, they were later arbitrated into a final coding. Explanations of the coding schemes and coding process can be found in Bilda et al. (2006).

3.3. ANALYSIS OF IDEA LINKS

Linkography is a system of notation and analysis of design processes that focuses on links among design ideas, developed by Goldschmidt (1990, 1997, 2003) and extended by others (Van der Lugt 2003, Kvan and Goa 2005, Kan et al. 2006). A linkograph is constructed by discerning the relationships among the design ideas (called moves) to form links. It can be seen as a graphical representation of a design session that traces the associations of every design move. The design process can then be looked at in terms of the patterns in the linkograph which display the structural design reasoning.

Goldschmidt (1992) identified two types of links: back-links and fore-links. Back-links are links of moves that connect to previous moves and fore-links are links of moves that connect to subsequent moves. Conceptually these are very different: "back-links record the path that led to a move's generation, while fore-links bear evidence to its contribution to the production of further moves" (Goldschmidt 1995). The process of linking the ideas and special consderations in SK and BF protocols has been discussed in Bilda et al (2006).

4. Does Sketching Off-Load Visuo-spatial Working Memory?

In this section we present the change in the architects' cognitive activities along the timeline of the design activities under BF and SK conditions. Each design session was divided into two periods; the first 20 minutes (period 1) and the remaining time in the session (period 2). The reason for dividing the sessions into two periods is based on the assumption that cognitive load is accumulated over time; therefore the cognitive load might be less in period 1 and more in period 2.

There are two initial assumptions regarding the change in cognitive activities of the participants:
If cognitive activity increases or remains the same from periods 1 to 2, then cognitive load has no impact.
If cognitive activity decreases from periods 1 to 2, then this drop is possibly caused by the cognitive load.

After completing the coding process, each design session contained more than 1,000 cognitive actions. We summed the total number of cognitive actions in each 5 minute interval. This was calculated by adding up the frequencies of actions in the segments of a five minute interval. Then the mean and standard deviation of these data points were calculated for each session. In order to be able to observe trends of cognitive activity and compare the changes under BF and SK conditions, cognitive activity rates were normalized. The normalized frequency of cognitive actions in each five minute interval was calculated using the mean and standard deviations of each session (Normalized A = (Mean - A)/standard deviation).

Table 1 presents results for A1's SK and BF sessions. The bottom two rows show the mean and standard deviation statistics, and the last two columns in Table 1 show the normalized frequencies calculated for each five minute interval.

Insert Table 1 here

For each architect's sessions, normalized frequencies of cognitive activity in five minute intervals were documented and this data was used to plot the normalized activity graphs for observing the nominal change in cognitive activity. Table 2 shows the sum of normalized cognitive activity data points in the periods 1 and 2. A1's normalized activity values under the SK condition add up to 0.9 in period 1 and to -0.9 in period 2. The overall activity decreases from periods 1 to 2.

Table 2 shows the magnitude of the variance in normalized activity values between the first period and the second period of the sessions. The magnitude of variance is equal to BF – SK of the values in periods 1 and 2, and is (-6 – (-2) = -4) for A1. Note that the magnitude of variance has a minus sign if the activity is decreasing and a plus sign if the activity is increasing from the first period to the second. For example, A1's overall cognitive activity is decreasing under the SK condition (-2) and under the BF condition (-6). The decrease under the BF condition is greater than the decrease under the SK condition, and this difference is shown as "BF – SK", a negative value of -4 in Table 2.

Insert Table 2 here

The magnitude of variance in overall cognitive activity is noticeably greater under the BF conditions compared to SK conditions, for all participants' sessions. The magnitude of the change under the BF conditions is between -4 and -6, which is significant in terms of the range of the normalized values in general. In cases where the variance is negative under both conditions, then the decrease under the BF condition is three to five times greater than the decrease under the SK condition. For A3, A4 and A6 the variance under the SK condition is positive, which indicates an increase in sketching performance, while there is a drop under the BF condition. This trend also shows that the drop under the BF condition is significant for A3, A4 and A6.

Figure 1 shows the second order polynomial fit of the normalized overall cognitive activity during the SK and BF sessions for each participant. Every node of the trend line represents the total number of cognitive actions in a five minute interval. The normalized trends fluctuate considerably making it difficult to determine similarities or differences. The trend lines of the normalized cognitive activity were approximated to a second-order polynomial fit. The reason for choosing a second-order polynomial rather than a linear one is to demonstrate the effect of fluctuations in the trend lines. Higher R^2 values were obtained when polynomial fits were applied to the trend lines.

Insert Figure 1 here

The polynomial fits showed a similar form for the group of A1, A2 and A5, and for the pair of A4 and A6, as illustrated in Figure 1. A3 demonstrated a different trend to the others. Figure 1 activity curves for the six architects' BF and SK sessions show that the BF activity generally slows down more than the SK activity after around halfway along the timeline of the designing sessions. Figure 1 also shows a consistent decrease in BF activity for all participants in the second period, and this decrease is significantly greater than a decrease in SK activity.

In the following sections, the architects' BF and SK activities in perceptual, functional and evaluative categories are analyzed in five minute intervals and in the first and second periods of the designing sessions. The analysis approach is similar to the analysis of overall cognitive activity, where the average polynomial trends of SK and BF perceptual activity are plotted and the variances in cumulative normalized perceptual activity in the first and second periods are compared.

4.1. PERCEPTUAL ACTIVITY

Table 3 shows the sum of normalised perceptual activity values in periods 1 and 2, and the magnitude of the variances under SK and BF conditions. The perceptual activity increased (positive sign in magnitude of variance) from period 1 to period 2 under SK conditions for A1, A3, A4 and A6. The perceptual activity remained unchanged under the SK conditions for A2 and A5 (variance is zero).

Insert Table 3 here

The perceptual activity slowed down (negative variance) from periods 1 to 2 in the BF designing sessions of A1, A2, A5 and A6. Only A4's perceptual activity increased (magnitude of variance is 2) in his BF session. For the other five participants, one can observe significant drops in BF perceptual performance compared to SK perceptual performance (A1, from 2 to -6; A2 from 0 to -7; A3 from 4 to 0; A5 from 0 to -5; and A6 from 5 to -1). The performance drop under the BF condition was observed for five of the six architects.

Figure 2 shows the second-order polynomial fit of the normalized perceptual activity over the five minute intervals for the six architects. For A1 and A6 the BF activity curve intersects with and drops below the SK activity curve around the twentieth minute along the timeline of the designing session, Figure 2. For A2 and A5, the BF activity curve drops below the SK activity curve just after the thirtieth minute for A2 and A5; around the fifteenth minute for A3 and A4. The BF activity curves dropped below the SK activity curves at different points for each architect. These points indicate for how long during BF designing each architect was able to handle the cognitive load.

Insert Figure 2 here

4.2. FUNCTIONAL ACTIVITY

Table 4 shows the sum of normalised functional activity values in periods 1 and 2, and the magnitude of the variances between these values under SK and BF conditions. There is a decrease in functional activity from period 1 to period 2 under both BF and SK conditions of the five architects. The five architects' attention to the basic functions of the building was less in the second period under BF conditions. Different from other participants, A6's functional activity remained unchanged (magnitude of variance is zero) under his BF condition.

The BF–SK differences in functional activity (Table 4) are -1, -2 or -3, which are relatively low compared to BF–SK differences in perceptual activity, Table 3. It can be concluded that the architects' functional activity variances under BF and SK conditions were not noticeably different.

Insert Table 4 here

4.3. EVALUATIVE ACTIVITY

Table 5 shows the sum of normalized evaluative activity values in periods 1 and 2, and the magnitude of the variance between these values under SK and BF conditions. Under the SK condition, the evaluative activity of A1, A3 and A4 is increasing (the magnitude of variance is positive: 4, 5, 4) from period 1 to period 2. For A2, A5 and A6 the evaluative activity under the SK condition is decreasing (minus sign). Under the BF condition, the evaluative activity decreases for A1 and A5, remains unchanged for A3 and A6, and increases for A2 and A4 from periods 1 to 2.

For A1 and A3 the evaluative activity under the BF condition drops below their evaluative activity under the SK condition, and the drop is significant for A1, and for A3. Evaluative activity for A2, A4, A5 and A6 increased from periods 1 to 2 during their BF sessions; the so-called cognitive load did not have a negative effect on their evaluative performance.

Insert Table 5 here

4.4. SUMMARY

The results of this section can be summarised as follows:

- For each participant the overall cognitive activity under the BF condition dropped significantly below the overall cognitive activity under the SK condition from the periods 1 to 2.
- For five of the six architects (excluding A4), the perceptual activity under the BF condition drops relative to the perceptual activity under the SK condition from periods 1 to 2.
- For five of the six architects (excluding A6), the functional activity under the BF condition drops relative to the functional activity under the SK condition from periods 1 to 2.
- Four of the six architects' evaluative activity under the BF condition increased compared to their evaluative activity under the SK conditions.

The variance from the first to the second period in overall cognitive activity under the BF conditions was below the variance under the SK conditions for all participants. It was assumed that the drop may be due to the higher cognitive demands of visuo-spatial tasks in working memory when the task was carried out using mental imagery only. Thus Hypothesis 1 can be accepted; sketching off-loaded the overall cognitive activity during conceptual designing sessions of the six expert architects.

5. The Impact of WM limitations on Idea Development

Idea development of the six architects was investigated by analyzing the linkographs of the BF and SK sessions. The basic assumption to test the impact of WM limitations on idea development is that the cognitive load is accumulated over time. We would expect changes in the way ideas were developed in the second half when compared to the first half of the sessions. The features of the idea development we have analyzed were the link density (link index) and the link diameter.

5.1. ANALYZING LINK DENSITY

We again used the two periods. The link index (LI) in the first period was calculated by dividing the total number of links at the Nth segment by N (N is the segment number where first period ends). The LI in the second period is the total number of links that occur only between segments N to K divided by K-N (K is the total number of segments of the session). Link indices were calculated for the two periods of each architect's BF and SK design sessions. The link index represents the density of new idea links established in each period, it refers to the (new) idea generation rate in each period.

Table 6 shows the LI values in the first and second periods of the design sessions; and in the adjacent column the sign of the LI differences. A positive sign indicates that the idea generation index increased, and a negative sign indicates it decreased from periods 1 to 2. During the SK sessions of the first three architects LI values increased from periods 1 to 2, Table 6. During the SK sessions of the second group of architects, LI values decreased from periods 1 to 2, Table 6. Comparing idea generation index differences between the two periods of the SK sessions indicated different results for the two groups of architects. During the BF sessions of all architects, LI decreased from periods 1 to 2. This result indicates that the idea generation consistently slowed down in the second period of the BF sessions. The result does not indicate whether this slow-down-effect was due to WM limitations, since the same effect was observed in the SK sessions (control condition) of the second group of architects.

We observed whether idea generation indices measured in periods 1 and 2 were noticeably different under the SK and BF conditions. The LI differences (from periods 1 to 2) under SK conditions were not noticeably different for four architects (A4 and A5 are exceptions). The LI differences under BF conditions were noticeably different for A2, A4, A5 and A6. During these four architects' sessions the LI values decreased significantly from periods 1 to 2. This result indicates that the slow-down of idea generation was relatively noticeable under the BF conditions compared to SK conditions.

Insert Table 6 here

In summary, the change in idea generation rates during sketching showed different tendencies for the first and second group of architects. The results indicated that the change in idea generation index from periods 1 to 2 was noticeably different during the BF sessions of 4 out of 6 architects. In this section we have shown that the idea generation rate significantly slowed down when the architects were not able to sketch. It was also shown that the idea generation rate could slow down when the architects were able to sketch. However, the slow-down-effect was not noticeable during SK sessions of these 4 architects. Thus Hypothesis 2 can be accepted; the idea generation rate slows down along the timeline of the design activity when designers are not allowed to sketch.

Testing whether working memory/short-term memory limitations have an impact on idea development needs further analysis of the linkographs. The measures of idea generation index did not demonstrate how far the links reached along the timeline of the design sessions. The next stage will be testing the variance of link diameters under BF and SK conditions.

5.2. ANALYSIS OF LINK DIAMETERS

The diameter of a link is defined as the distance it travels between the two moves it connects. Diameter indicates how far a link reaches along the timeline of the design activity. For example, if there is a link between the third and forty-fifth moves, the diameter would be 42. Diameter analysis of the links may indicate whether the working memory resources are used efficiently; the further the links reach along the timeline of the activity, the more efficiently the working memory is used.

The average diameter of the links in a session was calculated by finding the distances between all links in the session and dividing that number by the total number of links. Table 7 shows the largest and the average diameters under BF and SK sessions in the first two columns. The third column shows in which condition the average diameter of the links were larger.

Insert Table 7 here

The bottom two rows of Table 7 show the link diameters averaged for the six participants under BF and SK conditions. The value of average SK (21.5) is very close to the value of average BF (21.3). The SK1 session had the largest average link diameter amongst all sessions. This means that in the overall session, A1 was able to remember and re-use her more distant ideas. Four out of six architects had relatively larger link diameters under the SK conditions, compared to the link diameters under their BF conditions (A1, A2, A4, A5). A3 was able to keep track of her ideas and revisit them more efficiently under her BF condition (diameter: 11.4 in SK, diameter: 21.3 in BF). However the overall comparison between BF and SK sessions does not indicate any significant difference. The paired t-test between the average length of the link diameters of the BF and SK sessions showed no statistically significant difference (two-tailed probability = 0.94).

The average length of link diameters was not significantly greater in any of the SK sessions. Additionally the average values of the largest diameters showed no significant difference between BF and SK conditions (21 and 21 moves each). Hypothesis 3 can be rejected; designers do not necessarily need sketches to remember and keep track of their design ideas.

Table 8 shows the average link diameters (LD) calculated in the first period and in the second period. In this calculation, the diameters that go beyond the boundaries of the periods were excluded, such that the diameter of the links in the second periods should have their start and end points in the second period. The same rule applies for the links in the first period. The links which connect a move in the first period to a move in the second period are not included in the count of first period LDs, nor second period LDs.

Insert Table 8 here

Table 8 shows a significant difference between first period LDs and second period LDs of the BF sessions on average (12.0 and 8.9). This means that the LDs in first period of BF sessions reach a longer distance than those in the second period. We suggest that the idea development in the second period had been relatively incremental, rather than involving big jumps between the ideas. This rule, however, did not apply to all architects; A2 and A6 were the exceptions. BF2 and BF6 LDs in the second period (11.8; 12.5) were larger than the LDs in the first period (10.0; 10.2) although the difference is not noticeably significant. For the other BF sessions, LDs in the second period were significantly smaller than the LDs in the first periods.

The SK sessions in Table 8 shows no significant difference between first and second period LDs on average (11.3 and 11.3). A1, A2 and A3 demonstrated similar values of LDs in the first and second periods (SK1, 12.7 and 12.8; SK2, 12.7 and 11.8; SK3, 7.8 and 7.7). In the SK4 and SK6 sessions, second period LDs are larger than the first period LDs. In the SK5 session, second period LD is significantly smaller than the first period LD.

Under the SK condition, the diameters of links in the first and second periods are similar (11.3) on average. Under BF conditions, the diameters of links in the first period are larger than those in the second period (on average). Four out of the six architects' BF sessions showed that the reach of idea links was significantly smaller as the design progressed. This was confirmed by measuring the link diameters in the first and second periods of the BF sessions. Hypothesis 4, stating that short-term memory limitations have an impact on idea development, can be partially accepted.

6. Discussion and Conclusions

We analyzed the cognitive activity differences in BF and SK design sessions by dividing the sessions into two periods. It was observed that each architect's overall cognitive activity under the BF condition dropped below her/his activity under the SK condition after approximately 20 minutes during the timeline of the design sessions. We assumed that the drop may be due to the higher cognitive demands of visuo-spatial tasks in working memory when the task is carried out using mental imagery only. The implication of this assumption is that externalization of the visuo-spatial relationships between imagined objects/things would reduce the mental effort for visual reasoning required in design.

The drawings/diagrams enable designers to see and reason about perceived relationships. This might be difficult without making the relationships explicit by drawing. However, Anderson and Helstrup (1993) found that sketching does not add significantly to imagery-based discoveries using mental synthesis. Verstijnen et al (1998) conducted similar experiments with industrial design students requiring imagery operations such as synthesis, manipulation and inspection of relatively simple figures. They found that sketching usually was needed if the operations could not be done within mental imagery alone, or if the operations were much easier to perform externally. In a follow up study Kokotovich and Purcell (2000) conducted experiments with designers and non-designers and obtained results similar to Anderson and Helstrup (1993). In these studies the given tasks were quite simple compared to what the architects in the current study had to deal with under the BF condition. Kokotovich and Purcell (2000) indicated that designers were able to effectively use drawings for creative discoveries while non-designers were not. Their result emphasized the importance of experience in utilizing drawings as a means of providing useful cues for thinking and problem solving. Similarly in our study, the use of sketches was an important issue as a means of thinking and visuo-spatial reasoning during designing. The expert architects under the BF conditions accumulated a large amount of visuo-spatial information in the first 20 minutes of the design sessions. Then the maintenance and transformation of this information might require more effort which might result in an overload of VSWM. Possibly the reason for drop in overall cognitive activity is this cognitive load.

Bilda and Gero (2006) investigated the total number of cognitive actions under BF and SK conditions for the six architects, and showed that there were no significant differences. This means that the cognitive activity was similar across the BF and SK conditions; however the work reported in this paper has demonstrated that there was a significant drop in the second periods of BF sessions. The reason for the overall similarity was that the architects started with much higher rates of cognitive activity in the first half of BF designing, compared to the rates under the SK conditions. Only after 20 minutes into the BF session did the rate of cognitive activity drop below the rate under the SK condition. In addition, the impact of VSWM load was observed on perceptual activity more than the impact on functional and evaluative activity. Thus the consistent rates of concept generation and evaluation helped the architects to come up with satisfactory design solutions using imagery alone, despite the working memory limitations.

The results also showed that the perceptual activity improved under the SK condition over the timeline of the activity, while it decreased under the BF conditions due to the cognitive load from first to second periods in the design sessions. VSWM literature supports this finding, where cognitive load is produced due to using executive function resources (Baddeley et al. 1998). Why does perceptual activity use up more executive functioning? This is probably related to the difficulty of retaining images in mental imagery. Once the mental images are generated they fade away quickly (Kosslyn 1980). Even though the images fade away, they can be retrieved from a temporary storage and regenerated again, however this mechanism needs attention, and attention is attained by the functioning of the central executive (Pearson et al. 1999).

The variances in functional activity under BF and SK conditions of the six architects were not significantly different compared to their perceptual performance variances. This result implies that sketching may not have necessarily improved production of meaning, however it improved perceptual activity. This result also suggests that the cognitive load may be related to perceptual activity rather than the functional activity. The visuo-spatial tasks which require the use of central executive resources create the cognitive load, rather than the concept /meaning formation.

Under the BF conditions, four architects were able to judge, reason about their designs, and evaluate the possible solutions. Table 5 showed that the variance in their evaluative activity was positive, from the first to the second period during their BF sessions. The so-called cognitive load did not have a negative effect on their evaluative performance. This strengthens the claim that the cognitive load was related to perceptual activity, not to production of meaning or evaluation of design solutions/ ideas.

The impact of working memory load on idea development was tested by measuring and comparing the idea generation index values and link diameters from periods 1 to 2 in the linkographs. During the BF sessions of the six architects, idea generation indices were found to decrease significantly from periods 1 to 2. Not being able to sketch significantly slowed down the generation of new ideas, thus we maintain that sketching off-loads working memory. The tendency of architects to generate new ideas was in parallel to their overall (and perceptual) cognitive activity; both idea generation and overall/perceptual activity slowed down in the second periods during the BF sessions.

The average length of link diameters in the first and second periods of SK sessions did not show any difference, while in the BF sessions, link diameters in the second period were found to be significantly smaller compared to the diameters in the first period. One interpretation of this result is that in the BF sessions, while more ideas were accumulated along the timeline and cognitive load was increased, architects' did not tend to go back and forth between the ideas that were developed in the beginning and the ideas developed towards the end of the session. They played with the ideas within their proximity, rather than exploring the ideas further along the timeline of the session which required bigger jumps. Bigger jumps between ideas might require more memory resources, since architects depended solely on their memory under their BF conditions and were not able to use sketching as an extended memory. Consequently the impact of the working memory limitations was the architects' tendency for developing ideas within a shorter reach after half way through the BF design sessions.

6.1. WM LIMITATIONS OR IDEA SATURATION?

Working memory (WM) is hypothesized to be a model for STM, thus the duration one can hold and process information should be quite short. For example remembering a telephone number immediately after it has been told can be an example to testing the verbal component of WM resources in cognitive psychology research. The examples of testing the visuo-spatial component of WM are similar to Kosslyn's (1980) experiments such as image maintenance, image scanning, or rotation, where subjects are initially shown the images and then are asked to remember and process the visuo-spatial information they hold. Designing blindfolded is a more complex process and obviously requires more cognitive resources and processes than holding an image in the mind's eye. In the current study architects were asked to develop a design of a building in a 45 minute session. The BF sessions are more similar to the experiments conducted with expert chess players where they were required to hold and process visuo-spatial information for extended periods (Saarilouma 1998).

Long-term working memory has been identified as the use of expertise imagery with an extended WM capacity (Ericsson and Kintsch 1995). Extended capacity could allow the designers to hold and process more conceptual and visuo-spatial information. Then there is a possibility that the WM limitations might not be the reason for the impacts observed on idea links during the second periods of the BF sessions. An alternative interpretation could be as follows: the decrease in link diameters in the second period of BF sessions could be due to saturation of ideas. Concepts and ideas are accumulated and revisited along the timeline of the design session, however, the designer might think s/he had established a good solution for her/his design, consequently in the remaining time s/he might continue producing ideas that would support and add to that "good" design solution. Thus the architect might not perform big leaps, because the design solution is saturated with concepts. A2 and A6, who demonstrated larger idea diameters in their BF sessions, did not settle their design solution earlier during the process, but went back and forth between the range of ideas/alternatives throughout the session, until the end. The content analysis of their sessions also showed that they constructed most of the basic concepts and the main building layout in the later stages compared to the other four architects.

Kan et al. (2006) measured how randomly the links were distributed in the six architects' linkographs; describing this measure as the link entropy. Backward, forward, horizontal and overall link entropies were measured separately in the first and second periods of the BF and SK sessions of the six architects. The results showed that the link entropies did not change significantly under BF and SK conditions. The condition of not being able to sketch was considered to put a cognitive load on the design process and affect the achievement of other tasks, such as continuation of idea development. The link entropy results showed that cognitive load did not have a significant effect on the randomness of idea development from periods 1 to 2 under the BF conditions. This result supports our alternative proposal that the observed effect may not be due to WM limitations but due to a state of idea saturation in the second periods.

6.2. CONCLUSIONS

We presented the cognitive activity differences of expert architects when they design in blindfolded and in sketching conditions. From the first 20 minutes of the session to the remaining time in the sessions, the overall cognitive activity in blindfolded condition dropped below the overall cognitive activity in sketching condition. We compared the magnitude of variance in the cognitive activity under the BF and SK conditions and showed that the differences are significantly larger in BF conditions. This supports the idea that use of imagery for extended periods could slow down the cognitive activity rate, due to higher demands of cognitive processing under the condition of use of imagery alone. During sketching, the cognitive activity rate does not dramatically slow down, possibly because external representations help reduce the cognitive load during the progress of the design activity. We conclude that sketching off-loaded the VSWM.

The cognitive load accumulated in the second period of the BF sessions had an impact on the rate of idea generation; the idea generation index significantly dropped in the second periods of BF sessions but not in SK sessions. Similarly, the link diameters in the second periods of the BF sessions were found to be significantly smaller than the LDs in the first periods. These results indicated that the overload of WM had an impact on idea development and maintained that sketching off-loads VSWM.

Despite the VSWM limitations the architects in the current study were able to complete their conceptual design in their minds without a need to off-load their WM. They were able to organize their cognitive resources effectively to achieve this result. Experts' use of tacit knowledge and the pre-existing chunks of spatial models from long-term memory could support the design process without the use of externalizations.

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9. Appendix

Common action categories

Perceptual Actions	
Pfn	Attend to the visual feature (geometry/shape/ size/ material/color/thickness etc) of a design element
Pof	Attend to an old visual feature
Prn	Create, or attend to a new relation
Por	Mention, or revisit a relation
Functional Actions	
Fn	Associate a design image/ boundary/part with a new function
Frei	Reinterpretation of a function
Fnp	Conceiving of a new meaning
Fo	Mention, or revisit a function
Fmt	Attend to metric information about the design boundary/part (numeric)
Evaluative Actions	
Gdf	Make judgments about the outcomes of a function
Gfs	Generate a functional solution / resolve a conflict
Ged	Question/mention emerging design issues/conflicts
Gap	Make judgments about form
Gapa	Make judgments about the aesthetics, mention preferences

FIGURES

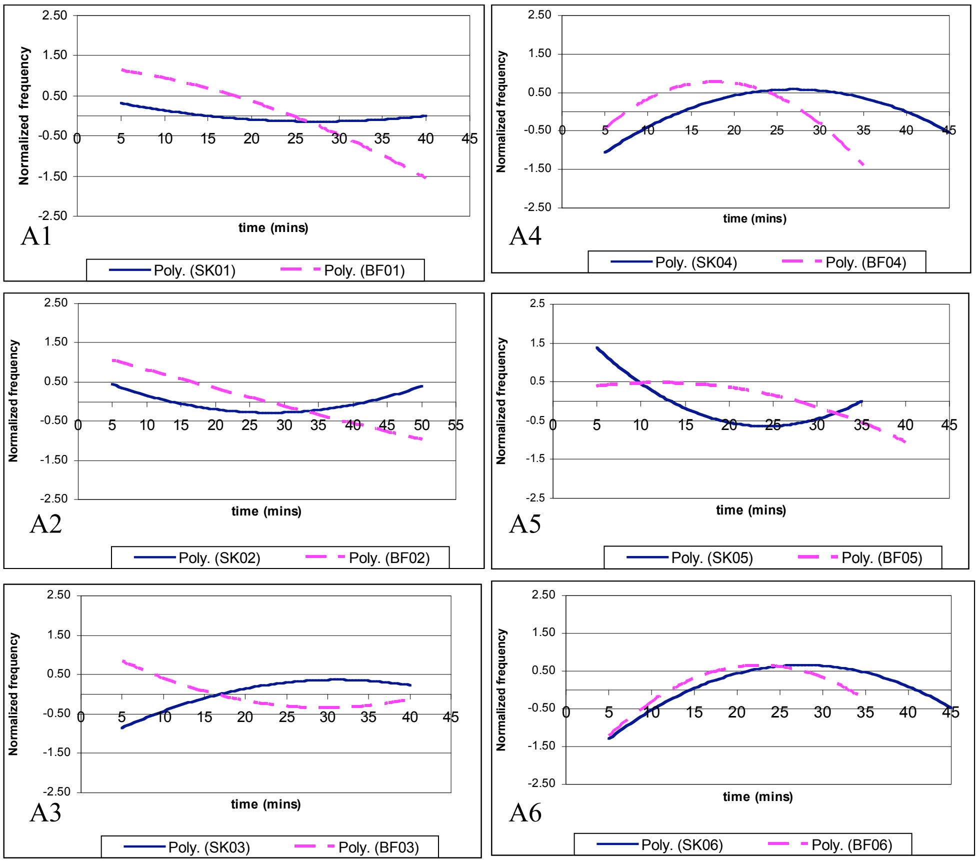

Figure 1 Polynomial fit of the normalised overall cognitive activity

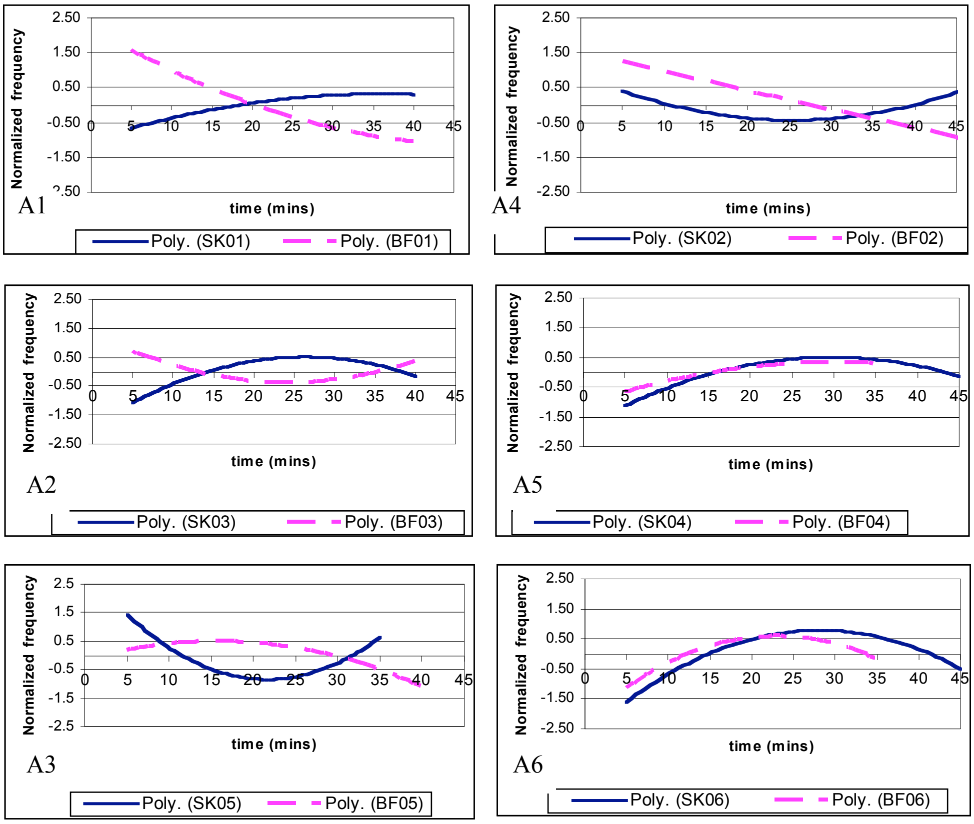

Figure 2. Polynomial fit of normalized perceptual activity

TABLES

Table 1 Sum of cognitive actions and normalised frequencies for A1

A1		Sum of cognitive action frequency		Normalised frequency	
Time intervals (mins)		SK1	BF 1	SK1	BF1
0-5		100	198	-0.25	0.86
5-10		116	209	1.54	1.18
10-15		109	201	0.76	0.95
15-20		99	173	-0.36	0.13
20-25		89	174	-1.48	0.16
25-30		109	148	0.76	-0.60
30-35		103	119	0.08	-1.45
35-40		93	127	-1.04	-1.22
Statistics	mean	102.2	168.6		
	std. dev.	8.9	34.3		

Table 2. Overall normalised cognitive activity variances from period one to two

		Normalised activity values		Magnitude of variance between two periods		
		SK	BF	SK	BF	BF – SK
A1	Period 1	0.9	3.1	-2	-6	-4*
	Period 2	-0.9	-3.1			
A2	Period 1	0.2	2.9	0	-6	-6*
	Period 2	-0.2	-2.9			
A3	Period 1	-1.9	0.7	4	-1	-5*
	Period 2	1.9	-0.7			
A4	Period 1	-1.1	1.7	2	-3	-5*
	Period 2	1.1	-1.7			
A5	Period 1	0.7	2.4	-1	-5	-4*
	Period 2	-0.7	-2.4			
A6	Period 1	-2.1	0.2	4	0	-4*
	Period 2	2.1	-0.2			

*Significant drop during BF session

Table 3 Perceptual activity variances from period one to two

		Normalised activity values		Magnitude of variance between two periods		
	Period	SK	BF	SK	BF	BF – SK
A1	Period 1	-1.0	3.1	2	-6	-8*
	Period 2	1.0	-3.1			
A2	Period 1	-0.1	3.7	0	-7	-7*
	Period 2	0.1	-3.7			
A3	Period 1	-2.0	-0.1	4	0	-4*
	Period 2	2.0	0.1			
A4	Period 1	-1.7	-0.8	3	2	-1
	Period 2	1.7	0.8			
A5	Period 1	-0.2	2.3	0	-5	-5*
	Period 2	0.2	-2.3			
A6	Period 1	-2.4	0.3	5	-1	-6*
	Period 2	2.4	-0.3			
* Significant drop in BF compared to SK session						

Table 4 Functional activity variance from period one to two

		Normalised activity values		Magnitude of variance		
		SK	BF	SK	BF	BF – SK
A1	Period 1	2.4	2.9	-5	-6	-1
	Period 2	-2.4	-2.9			
A2	Period 1	1.6	2.8	-3	-6	-3
	Period 2	-1.6	-2.8			
A3	Period 1	-0.1	1.0	0	-2	-2
	Period 2	0.1	-1.0			
A4	Period 1	0.9	2.6	-2	-5	-3
	Period 2	-0.9	-2.6			
A5	Period 1	1.0	2.5	-2	-5	-3
	Period 2	-1.0	-2.5			
A6	Period 1	1.1	0.1	-2	0	-2
	Period 2	-1.1	-0.1			

Table 5 Evaluative activity variance from period 1 to 2

		Normalised activity values		Magnitude of variance		
		SK	BF	SK	BF	BF – SK
A1	Period 1	-1.9	0.3	4	-1	-5*
	Period 2	1.9	-0.3			
A2	Period 1	1.1	-0.9	-2	2	4
	Period 2	-1.1	0.9			
A3	Period 1	-2.3	0.0	5	0	-5*
	Period 2	2.3	0.0			
A4	Period 1	-1.8	-2.8	4	6	2
	Period 2	1.8	2.8			
A5	Period 1	1.3	2.7	-5	-3	2
	Period 2	-1.3	-2.7			
A6	Period 1	2.0	0.2	-4	0	4
	Period 2	-2.0	-0.2			

* Significant drop in BF,

Table 6 Change in LI from first to second periods

	LI under SK conditions			LI under BF conditions		
Architect	Period 1	Period 2	LI diff	Period 1	Period 2	LI diff
A1	0.91	0.94	+	0.88	0.82	-
A2	1.06	1.38	+	1.30	0.83	-
A3	0.92	0.98	+	1.06	1.02	-
A4	2.05	1.22	-	2.02	1.35	-
A5	1.64	1.05	-	2.29	1.48	-
A6	1.58	1.50	-	2.21	1.73	-
LI: Idea generation index, LI diff: LI difference from period 1 to 2, + : increase, - : decrease						

Table 7 Link diameters

	Largest diameter	Av length of the link diameters	Av diameter relations
BF1	138	27.7	SK1>BF1
SK1	120	31.6	
BF2	101	19.0	SK2>BF2
SK2	159	22.6	
BF3	151	21.3	BF3>SK3
SK3	86	11.4	
BF4	153	23.2	Similar
SK4	138	24.4	
BF5	123	16.4	SK5>BF5
SK5	117	21.7	
BF6	111	20.0	BF6>SK6
SK6	146	17.0	
BF av	129.5	21.3	Similar
SK av	127.7	21.5	

Table 8 Link diameters (LDs) in first and second periods

	Period 1 LDs	Period 2 LDs	Compare LD in periods 1 and 2
BF1	13.0	7.1	P1>P2*
SK1	12.7	12.8	P1≈P2
BF2	10.0	11.8	P1≈P2
SK2	12.7	11.8	P1≈P2
BF3	14.0	8.3	P1>P2*
SK3	7.8	7.7	P1≈P2
BF4	10.7	5.0	P1>P2*
SK4	10.4	17.2	P1<P2
BF5	14.0	8.9	P1>P2*
SK5	18.2	8.4	P1>P2*
BF6	10.2	12.5	P1<P2
SK6	5.9	9.8	P1<P2
BF av	12.0	8.9	P1 > P2
SK av	11.3	11.3	P1 ≈ P2

* Significantly different, P1: Period 1, P2: Period 2