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DOES SKETCHING OFF-LOAD VISUO-SPATIAL WORKING MEMORY?

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Abstract. Empirical studies on visuo-spatial working memory show that the capacity of the visuo-spatial working memory is limited when visuo-spatial tasks are done using imagery. Externalization is needed to off-load the visuo-spatial working memory. For the same reason drawings and diagrams play an important role in designing. This paper presents the cognitive activity differences of three expert architects when they design in blindfolded and sketching conditions. It was observed that all participants' overall cognitive activity in the blindfolded condition dropped below their activity in the sketching condition, approximately after 20 minutes during the timeline of the design sessions. This drop in performance can be explained by higher cognitive demands in blindfolded conditions. We concluded that sketching off-loads the visuo-spatial working memory.

1. Introduction

A previous case study showed that expert architects were able to come up with a satisfactory design solution when they were not allowed to sketch (Bilda and Gero 2005). The study suggested that sketching might not be the only way to conceptually design 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". In other words sketching puts much less load on the cognitive processes needed to design. Evidence in working memory research supports that the cognitive load should be higher in a blindfolded exercise since image maintenance and synthesis of images requires more executive control resources (Pearson et al. 1999; Vecchi and Cornoldi 1999, Baddeley et al 1998).

2.Background

Imagery has been claimed to be the visuo-spatial sketchpad (VSSP) of the mind in the model of working memory (Baddeley 1986; Logie 1995). It is considered to be an alternative imagery model. In Baddeley's (1986) model the visuo-spatial sketch pad (VSSP) is likely to be related to visual perception and action while central executive is related to attention, control of action and planning. The VSSP is hypothesized to produce internal representations and process visual or spatial material. The role of working memory in design has been emphasized as a workspace for cognitive processes that retains information in visuo-spatial or verbal modes since designing involves the use of both verbally coded and visually coded knowledge. The workspace is hypothesized to provide coordination of visual, spatial and verbal information and retrieval from long term memory with a central executive.

In design research, use of imagery alone during the design activity is not considered to be sufficient since externalization is needed to allow design reasoning. Imagery studies have emphasized the role and necessity of externalizations for mental synthesis of parts/objects as well as for interpretation (Anderson and Helstrup 1993; Vertijnen 1998; Kokotovich and Purcell 2000). These studies provide evidence that maintenance, transformation or inspection of images/shapes would be very difficult unless they are externalized. 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 a large body of empirical evidence found in this literature, imagery activity intensively uses up working memory resources. Externalization is said to free up the working memory by storing/ externalizing the visuo-spatial information so that the other tasks can be carried out effectively. There is also evidence that the capacity of the visuo-spatial sketchpad itself may be limited and that performing any sufficiently complex visuo-spatial tasks would be impossible without the involvement of the executive functioning (Baddeley et al. 1998). Other empirical studies on visuo spatial working memory (VSWM) also show that the capacity of the VSWM is limited when visuo-spatial tasks are done using imagery (Ballard et al. 1995; Walker et al. 1993; Phillips and Christie 1997). Externalization is needed to off-load the visuo-spatial working memory. For this reason drawings and diagrams play an important role in designing. This paper reports on the cognitive activities of architects designing with and without the aid of sketching.

3. Method

The three architects who participated in the study (two female and one male) have each been practicing for more than 10 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.

The participants first engaged in a design process where they are not allowed to sketch. This phase is called the experiment condition where they receive design brief 01. Design brief 01 requires designing a residential for a painter and a dancer. In the experiment 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. After an interval of at least a month after the experiment condition the three architects were engaged in another design process where they were allowed to sketch. This phase is called the control condition where they receive design brief 02. Design brief 02 requires designing a house for a family with 5 children.

3.1. SEGMENTATION OF PROTOCOLS

The audio files of the concurrent verbalizations were transcribed and then segmented. The protocol was segmented using the same approach as for segmenting sketching protocols, i.e. by inspecting the designer's intentions (Suwa and Tversky 1997; Suwa et al. 1998). In the segmentation of sketch protocols, not only verbalizations but also video recordings of the sketching activity support decisions to flag the start and end of a segment. The drawing actions are inspected as cues for finding the changes in intentions. In the blindfolded condition information about the internal design representation state is extracted from the description of the current image or scene the architect talks about. The architect's attention may shift to a different part or aspect of the current image and this becomes the cue for change of intention. Keeping track of the changes in the descriptions of images/scenes supports our decisions to flag the start and end of a segment.

3.2. IMAGERY AND SKETCHING CODING SCHEMES

Recent research on sketching studies proposes that design thinking progresses at physical, perceptual, functional and conceptual levels in parallel (Suwa et al. 1998). Physical actions refer to drawing and looking, perceptual actions refer to interpretation of visual information, functional actions refer to attaching meanings to things, and conceptual actions refer to the planning of the actions and initiating actions for design decisions.

The imagery coding scheme borrows action categories from the sketching coding scheme. It consists of six action categories; visuo-spatial actions (VS), perceptual actions, functional actions, conceptual actions, evaluative actions and recall actions. We selectively borrowed actions from perceptual, functional, and conceptual action categories in the Suwa et al. (1998) coding scheme. The selected codes, Table 1, are the ones found to be highly correlated with drawing actions during the sketching activity of experts (Kavakli and Gero 2001).

TABLE 1 Perceptual, Functional, and Evaluative Actions

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

Perceptual actions category, Table 1, includes creating or attending to a new/old relationships between things, as well as (new or previously perceived) visual features of the things. Functional actions category refers to designer's actions when s/he attaches a meaning to an entity, or an image. Types of functional actions are listed in Table 1. The evaluative actions category has been formed during our explorations with the blindfolded and sketching design protocols. These actions refer to information at the conceptual level. During the think-aloud, we observed designers' self-talks in terms of idea evaluation or questioning cycles. In this inner dialogue some designers question ideas or emerging design issues (Ged) before evaluating them. They might generate a tentative a functional solution (Gfs) in this inner dialogue. The evaluation of the ideas is classified into three types:

1. evaluation based on a function that is previously introduced, i.e. evaluating by making judgments about the possible outcomes of the function (Gdf),
2. evaluation based on form of the design entity, in other words by making judgments about form (Gap), and
3. evaluation based on aesthetical preferences of the designer (Gapa).

3.3. CODING

In this study imagery processes are hypothesized to be similar to perceptual processes, the basic assumption is that all percepts are internal, where in sketching condition they are dependent on the act of drawing, and in blindfolded condition dependent on the internal representation. Since drawings are externalizations on paper, the perceptual features/ relations can be easily extracted and coded. One can question how we access the content of the internal representation. The imagery protocols demonstrate very detailed descriptions of images and scenes which refer to a dynamic internal representation. These verbalized descriptions make it possible to extract the relationships between design elements as well as the visual features. It is also necessary for the coder to keep track of the verbal descriptions of the imagery content and confirm them with the elements in the sketch produced at the end.

Each segment was time stamped, and coded with the related coding scheme. The complete audio/video protocol for each session was coded twice by the same coder with a one month period between the two coding passes. Then the codes were arbitrated into a final coding. The coding phase included a first run, a second run and finally the arbitration phase where codes are selected and accepted from first or second run in coding.

4. Results

After completing the coding process, we ended up with more than 1,000 cognitive actions for each design session. We summed the total number of cognitive actions in every 5 minute interval for each participant in both the sketch and blindfolded (BF) conditions. We ended up with 26 data points separately for sketch and BF conditions, where each data point indicates the total number of cognitive actions in 5 minute intervals. We tested if these points are statistically different, Table 2. The F-test probability is 0.0015, which means the variance in cognitive activity in 5 minute intervals is significantly different between sketch and BF conditions.

TABLE 2. F-Test for frequency of cognitive activity in 5 minute intervals

	Sketch	BF
Mean	139.6	150.6
Variance	377.6	1302.6
Observations	26	26
F	0.29	
P(F<=f) one-tail	0.0015	
F Critical one-tail	0.51	

4.1. HYPOTHESIS TESTING

If the variance in cognitive activity is significantly different between the two conditions then this may be due to the cognitive load in sketch versus BF conditions. As a next step we tested our hypothesis: sketching off-loads the VSWM. We divided each design session into two periods; the first 20 minutes and the remaining time in the session. 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 the first 20 minutes and more in the next 20 minutes. Then we looked at differences in normalized cognitive activity rates, whether cognitive activity was increasing or decreasing from period 1 to period 2. If cognitive activity was increasing in either condition, this means the participant is efficiently designing and cognitive load is handled. If the cognitive activity was decreasing in both conditions then we compare the magnitude of the drop of the activity between the sketch versus BF conditions.

We summed the total number of cognitive actions (X) in every 5 minute interval for each session. The mean (μ) and standard deviation (б) of each session are calculated. The normalized frequency (Z) of the total number of cognitive actions for each 5 minute interval was calculated as Z= (μ - X) / б. Table 3 shows first architect's (A1) sum of cognitive actions and the normalized cognitive action frequencies in each 5 minute interval.

TABLE 3 Sum of cognitive actions and normalized frequencies for A1

Architect A1		Sum of cognitive actions		Normalized values	
Time intervals (mins)		SK01	BF01	SK01	BF01
	0 - 5	143	198	-0.5	0.9
	5 - 10	162	209	1.1	1.2
	10 -15	161	201	1.0	0.9
	15 - 20	140	173	-0.7	0.1
	20 - 25	127	174	-1.8	0.2
	25 - 30	158	148	0.8	-0.6
	30 - 35	154	119	0.4	-1.4
	35 - 40	146	127	-0.2	-1.2
Statistics	mean	148.9	168.6		
	Std. dev.	12.12	34.25		

Table 4 shows the sum of normalized cognitive activity data points in the first 20 minutes (Period 1) and in the remaining minutes of the sessions (Period 2). A1's and A2's performance are above the average in the first 20 minutes during sketching (0.9, 0.2) and BF (3.1, 2.9) sessions. Their performance is below the average for the second period of the sketching (-

0.9, -0.2) and BF (-3.1 and -2.9) sessions. A3's sketching performance increases from first to second period (-1.9 to 1.9), while the same participant's BF performance decreases from first to the second period (0.7 to -0.7).

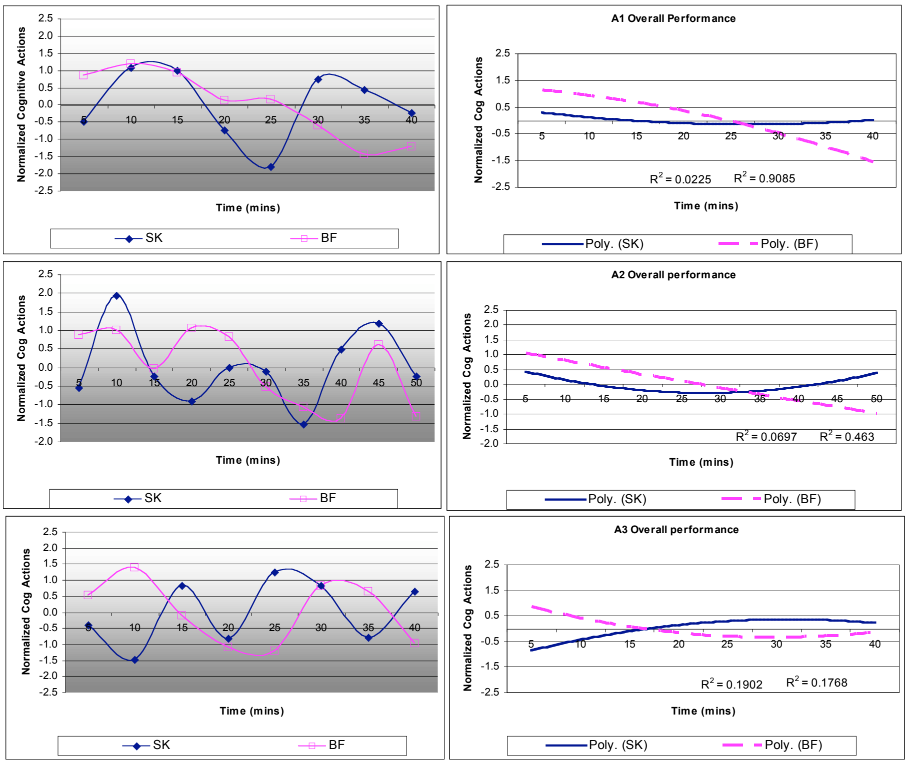
TABLE 4. Overall normalized cognitive activity variances from period one to two

Architect	Period	Sum of normalized activity values		Magnitude of variance between two periods	
		Sketch	BF	Sketch	BF
A1	First 20 mins	0.9	3.1	-2	-6
	Remaining mins	-0.9	-3.1		
A2	First 20 mins	0.2	2.9	0	-6
	Remaining mins	-0.2	-2.9		
A3	First 20 mins	-1.9	0.7	4	-1
	Remaining mins	1.9	-0.7		

The last two columns of Table 4 show the magnitude of the variance in normalized activity values between the first period (first 20 minutes) and the second period (remaining minutes) of the sessions. Note that the magnitude has a minus sign if the activity is decreasing and a plus sign if the activity is increasing from first period to the second. The magnitude of variance in activity is significantly larger in BF conditions compared to sketch conditions, for the three participants' sessions. For A1 the drop in BF condition is 3 times larger than sketch condition (-2 and -6), and for A2 there is no significant change for the overall sketching performance while there is a drop in the BF condition (0 and -6). For A3 the variance value is positive, which indicates an increase in sketching performance, while there is a drop in the BF condition. The variances in cognitive activity are significantly different between BF and sketch conditions for each of the three participants.

Figure 1(a) shows the normalized trends of cognitive activity in sketching and BF sessions for each participant. Every node of the trend line represents the total number of cognitive actions in a 5 minute interval.

The trends in the normalized cognitive activity fluctuated in both sketch and BF conditions for all participants, Figure 1(a). We applied 2nd order polynomial trend lines to obtain the average trend lines of the activities, Figure 1(b). The reason for choosing 2nd order polynomials rather than a linear trend line is to demonstrate the effect of fluctuations in the average trend lines. We obtained higher R^2 values when we applied polynomial trend lines.



(a) (b)

Figure 1. (a) Normalized values of cognitive activity over time, (b) polynomial trend lines of the activity

A similar pattern was observed in the polynomial trend lines of the normalized cognitive activity for the three participants, Figure 1(b). For A1 and A3 the rate of activity in BF sessions (dotted lines) starts at a higher rate and after around 15 minutes drops below the rate of cognitive activity in sketch sessions (continuous lines). For A2 a similar pattern was observed; after 30 minutes the rate of cognitive activity in BF session drops below the rate of activity in sketch session, Figure 1(b).

4.2. PERCEPTUAL ACTIONS

Second order polynomial trend lines applied to the normalized perceptual activity over the 5 minute intervals are shown in Figure 2 for the three participants. A common pattern was observed: perceptual performance in the BF condition dropped below the perceptual performance in sketching condition. For A1 and A2 the rate of perceptual activity in BF sessions starts at a higher rate and in the second period of the sessions it drops below the rate of perceptual activity in sketch sessions. For A3 the perceptual activity in BF condition dropped quickly and then increased towards the end of the session. Different perceptual performance trends were observed for the three participants.

The last two columns of Table 5 show the magnitude of the variance in normalized perceptual, functional and evaluative activity values between the first and the second periods of the sessions. The perceptual activity increased in sketch conditions (positive sign in magnitude of variance), while it decreased in BF conditions (negative signs) for the three participants.

4.3. FUNCTIONAL AND EVALUATIVE ACTIONS

Figure 3 shows polynomial normalized trend lines of the functional and evaluative activities in the sketch and BF conditions for the three participants.

Functional activities of the three architects are decreasing from first period to the second, in BF and sketch conditions (except for A3 where there is no change in sketch condition), Table 5, and functional activity performance in blindfolded condition drops below the performance in sketching condition, Figure 3(a). The magnitudes of the variances in functional activity are significantly different between sketch and BF conditions, for A2 and A3, however not for A1. As a result, functional activity significantly dropped for A2 and A3.

A common pattern was observed in polynomial trend lines of the normalized evaluative activity for the three participants, Figure 3(b); evaluative activity performance in blindfolded condition drops below the performance in sketching condition. The evaluative activity is increasing from period one to two in sketch and BF conditions, for the three participants. The variance in evaluative activity of the three architects from period one to two is significantly larger in sketch conditions (4, 4 and 5) compared to the BF conditions (0, 2, and 0).

4.4. SUMMARY OF THE RESULTS

In the blindfolded condition participants start with higher rates of cognitive activity in the first period of the sessions, and then the rate of cognitive activity drops below the average towards the end of the sessions. In the sketch condition this variance in cognitive activity is less, meaning that there is relatively more steady progress and activity compared to the BF condition.

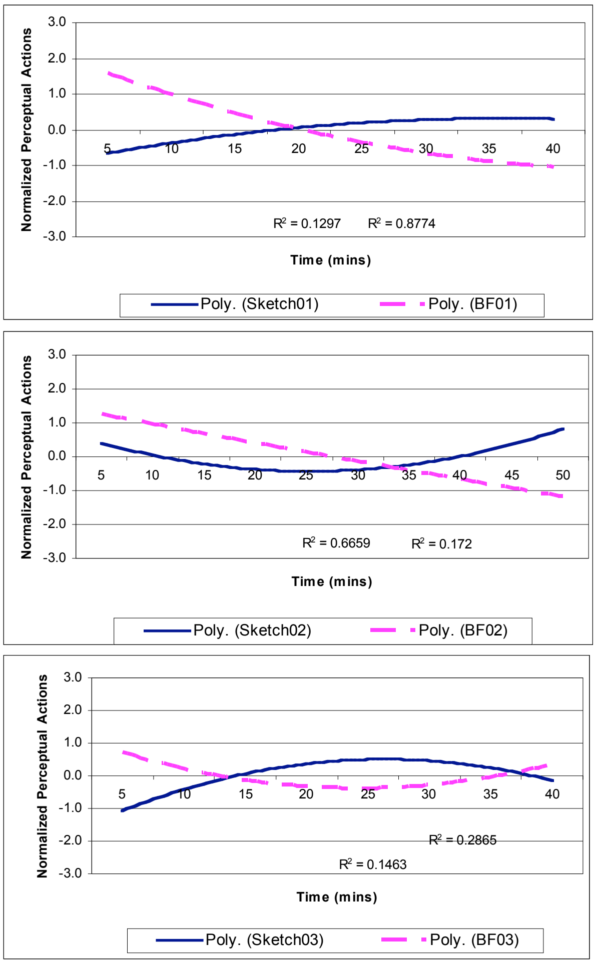


Figure 2. Normalized trend lines of perceptual activity over time

TABLE 5 Perceptual, functional, evaluative activity variances from period one to two

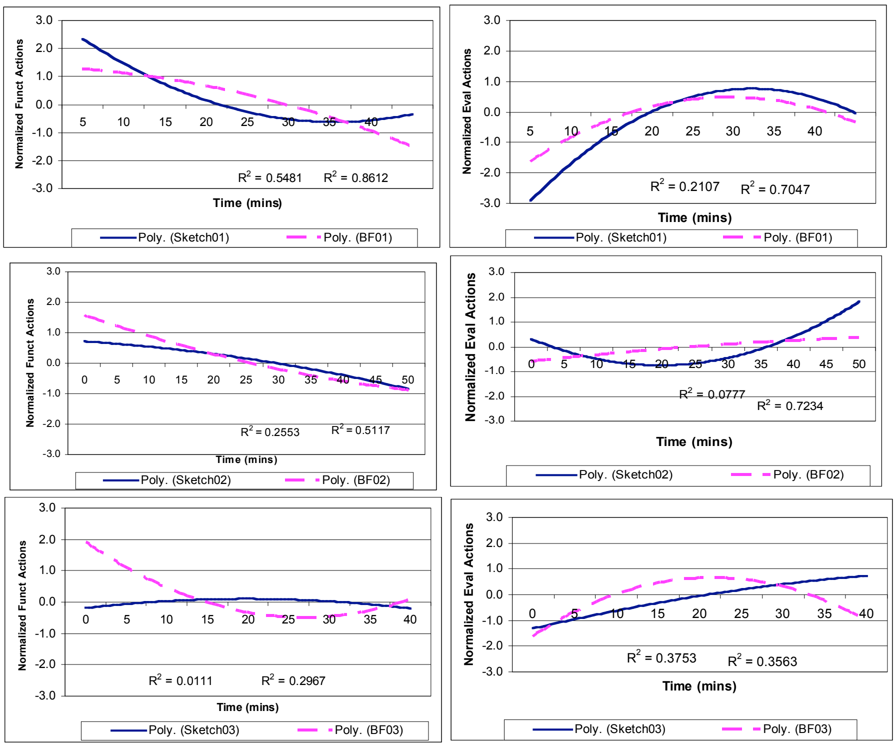
Perceptual Action Category		Normalized activity values		Magnitude of variance	
	Period	Sketch	BF	Sketch	BF
A1	first 20 mins	-1.0	3.0	2	-6
	remaining	1.0	-3.0		
A2	first 20 mins	-0.1	3.7	0	-7
	remaining	0.1	-3.7		
A3	first 20 mins	-2.0	-0.1		
	remaining	2.0	0.1	4	0
Functional Action Category		**Normalized activity values**		**Magnitude of variance**	
	Period	Sketch	BF	Sketch	BF
A1	first 20 mins	2.4	2.9	-5	-6
	remaining	-2.4	-2.9		
A2	first 20 mins	1.6	2.8	-3	-6
	remaining	-1.6	-2.8		
A3	first 20 mins	-0.1	1.0		
	remaining	0.1	-1.0	0	-2
Evaluative Action Category		**Normalized activity values**		**Magnitude of variance**	
	Period	Sketch	BF	Sketch	BF
A1	first 20 mins	-1.9	0.0	4	0
	remaining	1.9	0.0		
A2	first 20 mins	-1.9	-0.8	4	2
	remaining	1.9	0.8		
A3	first 20 mins	-1.9	0.0	5	0
	remaining	1.9	0.0		

The variance in activity in the three action categories can be summarized as follows:

perceptual activity increased in the sketch condition, while it decreased in the BF condition from the first to second periods;

functional activity decreased in both conditions, the drop of activity in BF condition is significantly larger compared to sketch conditions of the two participants; and

evaluative activity variance is positive and significantly higher in the sketch condition, compared to the BF condition; this implies that evaluative activity improved more in the sketching condition.



(a) (b

Figure 3. Normalized polynomial trend lines of (a) functional activity, (b) evaluative activity over time

5. Discussion

If sketching off-loads visuo-spatial working memory then the cognitive activity in the blindfolded condition should decrease as the design session progresses. We observed that in the second period of the BF sessions the overall cognitive activity dropped below the average and remained there. We also observed significant differences between sketch and BF conditions in the variance of the cognitive activity from the first to second periods of design sessions.

The variance from the first to second period in overall cognitive activity is negative and larger in BF conditions of the three participants than in the sketch conditions. We assume 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. Externalization of the visuo-spatial relationships inherited by the imagined objects/things may be reducing the visual reasoning required in design. The drawings/diagrams enable designers to see and reason about perceived set of relationships. This might be difficult without making the relationships explicit by drawing. Anderson and Helstrup (1993) found that sketching does not add significantly to imagery-based discoveries using mental synthesis. In that study the mental synthesis tasks given to the participants involved mental combination of separate simple figures and what was studied was the perception of what the synthesized image looked like using their imagery alone. The range of visuo-spatial tasks performed by the subjects in that study appears to be quite different to blindfolded architects, aiming to design a residential house. 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 following study Kokotovich and Purcell (2000) conducted experiments with designers and non-designers and obtained results similar to Anderson and Helstrup (1993). In that study the tasks given to the participants were hypothetical small scale design problems, the complexity of visuo-spatial reasoning were somewhat similar to what our blindfolded architects had to deal with. Kokotovich and Purcell (2000) indicated that designers were able to effectively use drawings for creative discoveries while non-designers were not. This 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 use of sketches was an important issue as a means of thinking and visuo-spatial reasoning during designing. In the blindfolded condition, our expert architects accumulated large amount of visuo-spatial information in the first 20 minutes of the design sessions. Not being able to externalize this information during the progress of designing could have produced a load on participants' thinking. Possibly the reason for drop in overall cognitive activity is this cognitive load.

The results show that sketching improves the perceptual activity over the timeline of the activity (see positive values in magnitude of variance in Table 5). However in the blindfolded condition perceptual activity decreased due to cognitive load from first to second period in the design sessions. VSWM literature supports this finding, where cognitive load is produced due to using the resources of executive functioning (Baddeley et al. 1998). Then 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, which means executive functioning (Pearson et al. 1999).

In contrast to the positive variance of perceptual activity, the variance in functional activity of the architects is negative in the sketching condition, Table 5. The functional activity in the BF and sketch conditions was not progressive along the timeline of designing (except for the A3 sketch condition, where there is zero variance in functional activity). This result implies that sketching does not add to (improve) production of meaning, however it improves perceptual activity. This result also suggests that the cognitive load may be related to perceptual activity rather than functional activity. The visuo-spatial tasks which require executive resources should create the cognitive load, not the concept /meaning formation.

In the BF condition, architects were able to judge, reason about their designs, and evaluate possible solutions. The results show that the variance in evaluative activity was positive, Table 5, from the first to the second period during the BF sessions. Architects' evaluative activity and design judgments were significantly higher in the sketch condition from first period to the second, Table 5. This means that sketching was a better medium for architects' design solution and idea evaluations. We observed positive or zero variance in evaluative activity in both conditions, which implies that there was no effect of cognitive load for this action category. We propose that the cognitive activity is related to perceptual activity, not to production of meaning or evaluation of design solutions/ ideas.

6. Conclusion

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 each time dropped below the overall cognitive activity in sketching condition. We compared the magnitude of variance in the cognitive activity in BF and sketch 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 in use of imagery alone. During sketching, the cognitive activity rate does not dramatically slow down, possibly because external representations help reducing the cognitive load during the progress of the design activity. We conclude that sketching off-loads the VSWM.

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