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Graphical Production of Complex Abstract Diagrams: Drawing Out Chunks and Schemas

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Abstract

What cognitive processes and strategies are used to reproduce complex abstract diagrams? Over ten sessions, a complex diagram was traced, copied, drawn immediately from memory and drawn after a delay. The five adult participants rapidly learned to make near perfect productions of the diagram. They converged on an approach that exploits chunks, which was used across all the modes of drawing, rather than a strategy that minimizes motor effort. They appear to use an overarching spatial schema to organize their access and production of the chunks.

Keywords: chunks, spatial schemas, drawing, tracing copying, graphical protocol analysis, Rey figure

Introduction

Drawing is a common human activity that has been rather neglected by Cognitive Science. Compared to the extensive studies on the nature of writing or the work on perception, reasoning and learning with diagrams, our understanding of the mechanisms underlying production of graphical artifacts at the cognitive level is relatively meager. There have been some notable studies. The classic work of van Sommers (1984) explored and described some of the underlying processes of drawing and Goel (1995) examined the more fluid nature of sketching particularly in the task of design problem solving. Some studies have used drawing as a means to investigate other aspects of cognition such as children's increasing flexibility in their use of schemas during cognitive development (Karmiloff-Smith, 1990) or the impact of alternative representational systems on conceptual leaning (Cheng, 2003).

Nevertheless, there are many questions and issues to be addressed concerning the underlying processes of drawing. The experiment reported here concerns well-structured diagrams. This experiment examines four modes of drawing: (a) *tracing* by drawing directly over the target diagram; (b) *copying* by transcribing the target diagram on to an adjacent blank sheet; (c) *immediate drawing from memory* when there has been exposure to the target diagram just prior but not during production; (d) *delayed drawing from memory* when the target has not been seen for some time. In this experiment what changes as the same diagram is drawn many times over an extended periods of many days is investigated, rather than, say, how generic drawing abilities change with cognitive development. How does the drawing process vary when the diagram does or does not have rich semantic content for the drawer? Van Sommers (1984) showed the interpretation that participants possessed influenced the order of production of the graphic elements in simple line drawings (consisting of about 5 lines and no more than two chunks). A complex abstract diagram without particular conceptual content was used as the stimulus in this experiment, which is shown in Figure 1. To what extent does drawing invoke the same cognitive structures and processes that are commonly implicated in other types of tasks? This study will consider the role chunks and use of schemas. Are there generic task strategies for drawing? If so what are they and how do they interact with the factors associated with the preceding questions?

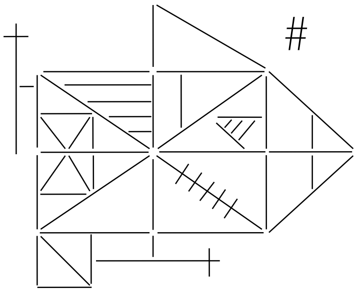


Figure 1: Modified Rey figure used in the experiment.

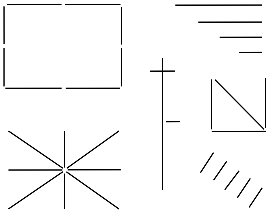


Figure 2: Six example patterns (not to scale).

The diagram in Figure 1 is a modified version of the Rey-Osterrieth Complex Figure (Meyers & Meyers, 1995). The original figure is used in a well-validated test of memory function. The modifications make it more suitable for our *graphical protocol analysis* approach to the study of graphical production, which is described below. The modifications include: inserting a space between the end of all lines, replacing circles and dots with lines, and breaking up long lines into shorter segments. The diagram has 56 lines (excluding the #).

Figure 2 shows a selection of the patterns of lines that appear to correspond to putative perceptual chunks, based on the normal scoring scheme used for the original Rey figure. The six patterns are shown in Figure 2 but Figure 1 incorporates 13. We presume that if participants are using chunks then the chunks may correspond to these patterns, which seem like plausible candidates, for example on the basis of the Gestalt principles of perception.

More precisely this experiment examines three sets of related questions in an exploratory fashion. First, to what extent is the process of drawing dominated by chunking? The use of an abstract diagram allows strategies that are not reliant on chunks to be manifest, as the stimulus does not have given semantic content that relates specific configurations of diagrammatic elements to particular conceptual chunks. The four modes of drawing were chosen in order to vary the likely use of chunks. Delayed drawing from memory is the most likely to involve chunking, because the lines of the diagram that share similar characteristics could be encoded as perceptual chunks. At the other extreme, one may expect that participants instructed to trace the target diagram 'as quickly and as accurately possible' might adopt a strategy that minimizes unnecessary movements of the pen by selecting successive lines that are in close proximity. If such a strategy is strictly used it will operate independently of whatever chunks the drawer perceives or retrieves from the memory. One might predict that the extent of chunk use in the copying mode of drawing will fall somewhere between that of the tracing mode and drawing from memory modes, as the stimulus is present but components must still be briefly remembered.

The second question: Is there a generic strategy (or strategies) for drawing complex abstract diagrams? Humans naturally adapt their behaviour in order to reduce the cognitive and physical effort expended on tasks, so one might expect that even moderately experienced drawers will adopt some generic approach to drawing that (to some extent) rationally organizes the process of graphical production. If the participants are not drawing in a haphazard or random fashion, what are they doing? One possibility, if they are not relying upon chunks, is some strategy that operates at the level of individual lines, such as selecting the nearest neighbouring line to be the next one to draw in order to minimize pen/hand movements and the need for higher level sequential planning.

The third set of question concerns learning. How will the process of drawing gradually change over time with improvements to the accuracy of the reproductions? To address this, the participants did ten repeated sessions of drawing each separated by a number of days. With repeated reproductions of the same complex diagram does the use of chunks change (if they are used) and how are the overall drawing strategies affected?

One means for probing chunking processes in drawing will be the *temporal chunk signal* that we have found in our studies using *graphical protocol analysis*. Our previous experiments on writing and drawing have demonstrated the existence of this signal that reveals the structure of chunks in memory. The signal has been found in the writing of simple sentences (Cheng & Rojas-Anaya, 2006) and artificial sentences (Cheng & Rojas-Anaya, 2008), in the writing of number sequences (Cheng & Rojas-Anaya, 2005), in the copying of mathematical formulae (Cheng & Rojas-Anaya, 2007), and in the production of simple geometric figures (Cheng, McFadzean & Copeland, 2001). The temporal chunk signal is based on the pause between successive pen strokes (i.e., the time between lifting the pen from the paper at the end of the previous mark and placing it down to begin the current mark). Significant differences between the duration of pauses at different levels of the hierarchy of chunks possessed by the participants were found across all types of task. The pauses for elements within a chunk (e.g., letter level, *L1*) are smaller than the pauses for the chunk itself (e.g., word level, *L2*). This finding is consistent with classic findings on chunking processes, for example, in chess (Chase & Simon, 1973), go (Reitman, 1976), electric circuits (Egan & Schwartz, 1979) and word lists (Bushke, 1976). However, the temporal chunk signal in graphical production is (remarkably) strong and robust with significant differences found between the chunk levels in the data for individual participants on a single trial; i.e., with no aggregation into groups. *Graphical protocol analysis* (GPA) is the term we use to describe our method for studying cognitive processes involving free-hand writing and drawing using the temporal chunk signal.

Another means for probing chunk structure, which also provides evidence on drawing strategies, is to examine the particular sequence of production of the elements within the different patterns of the target diagram. This will involve the analysis of whether drawing progresses in a consistent fashion with all the elements of each pattern being drawn together, or whether transitions occur between partially completed patterns.

Method

Participants

The participants were graduate students and research assistants at the University of Sussex. Each had a moderate amount of experience of drawing diagrams typical of graduates in technical subjects. One of the six participants originally recruited for the experiment was unable to complete the trials due to unrelated commitments. One participant was left-handed the rest were right-handed.

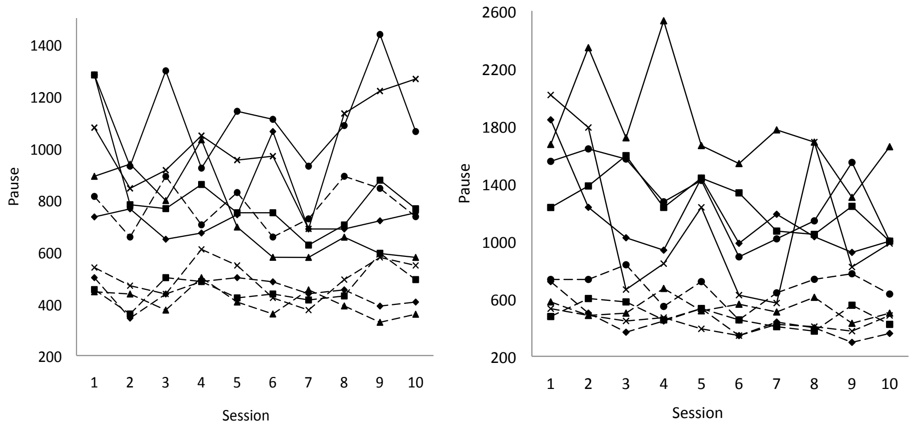
Apparatus

The single target stimulus is the complex abstract diagram in Figure 1. All drawing occurred with an inking pen on a sheet of paper taped to a standard graphics tablet (Wacom Intuos$^{2®}$). Specially designed drawing/writing analysis software, TRACE (Cheng & Rojas-Anaya, 2004), was used to record the writing actions, to extract the pen positions and times, and to compute the duration of pauses between drawn elements. Participants were instructed to produce drawings that largely filled an A4 page in landscape orientation. For the tracing mode, a copy of Figure 1 with faint grey lines was used. For the copying mode, a copy of Figure 1 was placed near the tablet for the participant to refer while drawing.

Procedure

There were ten sessions each lasting about 30 minutes. They were spaced no less than two and no more than seven days apart, with the precise timing dependent on the individual participant's availability. The time between the first and last sessions was between 3 and 10 weeks (No evidence was found that the different durations affected the overall results). In the first session the participant traced the diagram, then copied the diagram and finally drew the diagram from memory (immediate recall drawing). In the second and subsequent sessions the participant first drew the diagram from memory (delayed recall drawing). Then it was copied and traced, the order of which alternated with session. Finally an immediate recall drawing was done. For all drawings the participant first drew the hash (#) at the top right of the diagram to ensure that they were fluently drawing before any of the elements of the target was produced. The participants were told not to practice between sessions.

(a) Tracing (b) Copying



(c) Immediate drawing (d) Delayed drawing

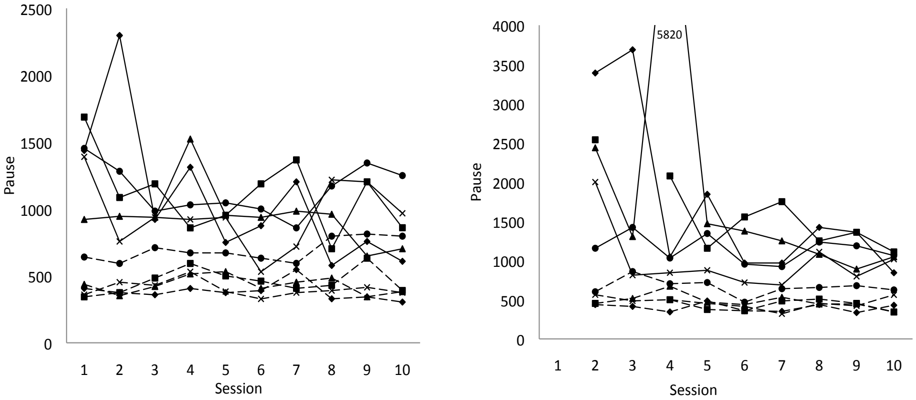


Figure 3: Median L1 within (dashed) and L2 between pattern (solid) pauses for each mode of drawing. (Each symbol type is a particular participant.)

Results

Overall performance

Participants overall success at producing the diagram was initially assessed by coding the errors made in their drawings in terms of omissions, commissions and structural (misshapen) errors at the level of whole patterns and elements within patterns. The structural errors are minor compared to the omissions and commissions errors. Except for the omission of one element by one participant in the very first session there were no errors with the tracing mode. In the copying mode there were slight structural errors in six of the drawings. For the immediate recall drawing mode there were (remarkably) few errors even in the first session. The worst participant omitted three patterns and six elements, but by the third session just two participants each made one structural error. With the delayed recall mode (beginning in the second session) the number of errors also declined from about 10-20 to near perfect drawings by the second or third attempt. The rapidity of reaching ceiling level performance was unexpected.

Between and within pattern/chunk pauses

On the assumption that if the participants were chunking the diagram they may be doing so in terms of the default patterns (Figure 2), each drawn line was coded either as *L2-between* or *L1-within* a pattern. A between pattern element is the first occurrence of any line of a particular pattern. All subsequent lines of the same pattern are within pattern elements. Figure 3(a)-(d) show the median values of the pauses for all the between and within pattern lines, for every participant, in every session, for all four modes of drawing. (There is no data for delayed recall drawing in session 1 and data for immediate recall drawing for one participant is missing due to experimenter error.) The solid line corresponds to L2 between pattern pauses and the dashed line to L1 within pattern pauses.

Simple visual inspection of the graphs reveals that in all 194 drawings the median of the L2 between pattern pauses is greater than the median of L1 within pattern pauses. If either were equally likely to be larger, then the probability of L2>L1 for all the 10 drawings of one participant in one mode is $p=0.5^{10}=.0001$, by the Binomial theorem. Separate t-test (one-tail, paired) comparisons of the L1 and L2 pauses over the 20 sequences of drawings for the 5 participants in the 4 modes were significant (p<.05 once; p<.01 once; 18 at p<.001). Further, t-test (one-tail, paired) comparisons of the pauses over the five participants for the 39 sessions (10 sessions by 4 modes minus 1) are significant, in all but two cases (p>.05 twice, p<.05 three times, p<.01 34 times.) (The outcomes of an ANOVA test is consistent with these results.) As longer pauses are associated with chunks (see above), it is clear that: (1) the participants are using chunks in the drawings in all modes; (2) these chunks largely correspond to the default patterns, some of which are shown in Figure 2.

The medians of the L1 within pattern/chunk pauses are similar across participants, sessions and modes of drawing. The L2 pauses are more variable. Overall, they are largest for delayed recall drawing, then for copying, immediate recall and least for tracing, respectively, 1453, 1336, 1047, 885 ms. Figure 4 shows the mean of the participants' median pauses. If there is a ¼ probability of any one of the modes being the shortest in any given session, then by the Binomial theorem, the chance of the tracing mode having at least nine of the smallest values is p=.00001. The mean of immediate recall drawing mode falls between the tracing mode and the other two modes in seven of the ten sessions, which by the Binomial theorem has as chance of p=.0031. T-tests (paired, one tail) of the between pattern pauses for all the pairs of modes across all the sessions were computed. The L2 pauses for tracing was shorter than each of the other three modes (p<.01 in all three). The L2 pauses for immediate recall drawing are shorter than for copying (p<.001) and for delayed drawing (p<.01). The difference between delayed drawing and copying is not significant. In summary, tracing has the shortest L2 pauses, immediate drawing the next, and copy and delayed drawing comparably long pauses.

The within pattern pauses are relatively constant over the sessions. There is an apparent decline of the magnitude of the between pauses over the sessions. The curves in Figure 4 show that the median L2 between pattern/chunk pauses declined over sessions. This is confirmed for the copying, immediate drawing and delayed drawing modes by the t-tests (one tail, paired) of the difference between the participants' first and last session median pauses (at p<.05 for each one). The particularly large drop between the second and third session magnitude of the delayed drawing model parallels the drop in the errors between the same sessions.

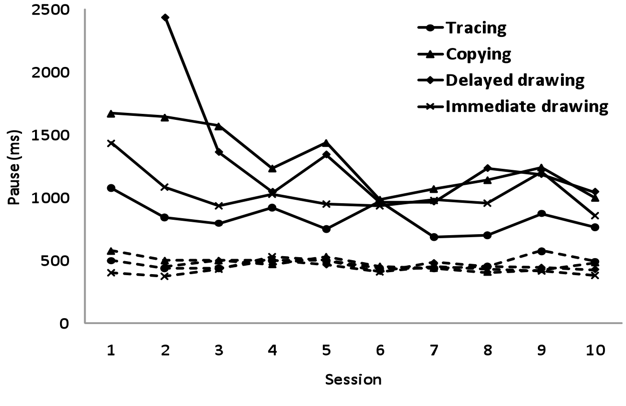


Figure 4: Mean of the L1-within (dashed) and L2-between (solid) pattern median pauses for all modes of drawing.

Sequences of drawing individual patterns

Another measure of whether the participants were treating the patterns as chunks is the number of times within a particular drawing that a switch occurs from the production of an element in one pattern to an element from another. The minimum possible number of switches is the number of patterns minus one (i.e., 12). The number of switches above this will be called the *transition count*, which is a measure of excess number of switches between patterns. When this is zero each and every pattern will have been drawn as a separate group that presumably are distinct chunks.

To obtain a sense of the transition count when chunks are not being used for drawing, the nearest neighbour drawing strategy was examined. It minimizes pen movements between lines using a strategy that selects the next line to draw by: (a) finding the undrawn line whose centre is the closest to the pen at the end of the just completed line; (b) moving the pen to the end of the selected line that is closest to the pen. The strategy was applied to the diagram using five different obvious starting points in Figure 1 (e.g., top left, centre) giving a mean transition count of approximately 12. Values less than this suggest of the use of chunks.

Figure 5 shows the mean transition counts across participants for the four modes across the sessions. By the second drawing in every mode the transition count has dropped to approximately half the value for the nearest neighbour strategy. A decline in the transition counts for each mode is apparent in Figure 5 and t-tests (one-tail, paired) between the first and last session over participants indicates that the drop is significant for the copying, immediate recall and the delayed recall drawing modes (p<.05, all modes), but not for the tracing mode.

Sequences of drawing groups of patterns

Inspecting all of the lines for each drawing over the ten ses-

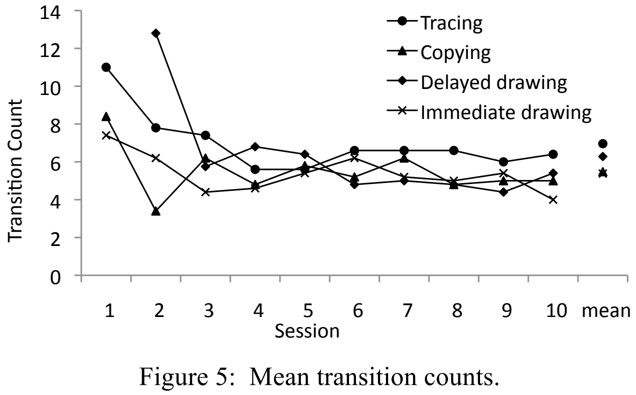


Figure 5: Mean transition counts.

sions, the groups of patterns are (very) often drawn together suggesting an amalgamation process of the individual patterns as drawing progresses over the sessions. One such group that often appeared in the drawings will be called the *frame* group, which consists of the large rectangle, triangle to the right, the top triangle and the lines radiating from the centre. The patterns within and beyond the large rectangle also appeared sometimes to be drawn as groups. To test whether these groups really have a substantive role in drawing, group transition counts were obtained for every drawing, in a fashion similar to the patterns but at the aggregated group level. Applying the nearest neighbour drawing strategy with different starting points gives transition counts in the range of 6 to 16.

Figure 6 shows the mean transition count over participants for each mode of drawing. The group transition count is substantially less than that for the nearest neighbour strategy indicating that the groups may have had a meaningful role. The measure is relatively constant for each mode with the exception of tracing. A t-test (one-tail, paired) on the first and last session of this mode has a large variance so the difference is not significant (p=.095).

Closer inspection of the sequence of patterns reveals that patterns from the frame group were always the first to be drawn in every diagram without exception. Twenty-three lines constitute the patterns of that group. For the tracing, copying, immediate and delayed recall modes the mean number (and range) of lines produced from the frame group before the start of any other groups were, respectively, 16.1 (11-21), 18.9 (16-21), 19.7 (18-22) and 19.8 (17-21). This suggests that frame group of patterns had a primary role in all of the modes of production, including the tracing mode but to a lesser extent than the others.

Discussion

With regard to the drawing of complex abstract diagrams using four modes of drawing, the questions posed for this experiment concerned: the role of chunking in graphical production; the existence and nature of generic drawing strategies; and the effects of learning over multiple sessions of reproducing the diagrams.

The experiment provides converging evidence that chunks have a central role in the drawing of one instance of a complex abstract diagram. The coincidence of longer pauses before the production of lines between the default patterns compared to pauses for lines within the patterns indicates that the participants were treating the patterns as chunks. The relatively low level of transitions counts also supports the claim that chunks had a causal role in the production of the diagram, because the participants on the whole tended to complete each pattern before moving to the next.

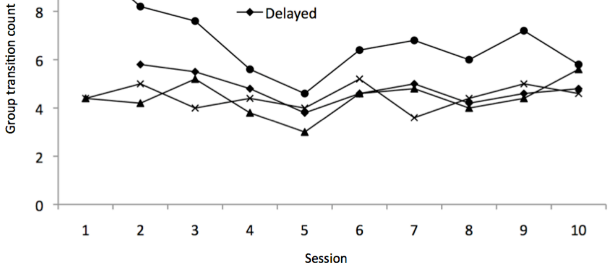


Figure 6: Transition count for groups of patterns.

The strong and robust temporal chunk signal that was found in other writing and drawing tasks using the Graphical Protocol Anaysis (GPA) method (Cheng & Rojas-Anaya, 2005, 2006, 2007, 2008; Cheng, McFadzean & Copeland, 2001) was also clearly found in this experiment. This extends the scope of the GPA for studying the nature of chunk-based phenomena in Cognitive Science. The magnitude of the L1 within chunk pauses was approximately 500 ms across all of the modes of drawing and fairly constant across sessions. In the latter sessions, the L2 between chunk pauses were approximately 900 ms. These times are longer than those found in the drawing of simple geometric figures in which L1≈400 ms and L2≈600 ms (Cheng, McFadzean & Copeland, 2001). Possible reasons for the difference are the great complexity of the stimulus in the experiment and the larger physical scale of the drawing.

As with the previous studies, the constancy of L1 pauses and the variability of L2 pauses suggest that the drivers of the observed effects are largely occurring at the chunk level. Tracing had the shortest L2 pause times, then immediate recall drawing, with copying and delayed recall drawing equally longest. A plausible explanation for why the immediate recall drawing L2 pauses is shorter than those for delayed recall drawing is the more recent and presumably greater activation of the chunks in memory for the former mode. The need to switch attention between the target diagram and drawing is one explanation for the greater L2 pauses for copying than immediate recall drawing. Tracing is the mode that one would expect to be the most different to the others, because the recall of chunks is not strictly necessary and shifts of attention to a remote target are not needed. Nevertheless the difference between L2 and L1 pauses indicates that chunking has an important role in the tracing mode. Notice in Figure 4 that the magnitude for copying converges with the immediate recall drawing line, which is consistent with the participants using their remembered chunks in the copying mode in later sessions. At a high level, chunks are being used substantially in the process of drawing as indicated by both the between pattern pauses being greater than the within pattern pauses and the low transition count (Figure 5). This raises an intriguing question for further research: Is the use of chunks during tracing (in the later sessions) somehow a more effective strategy than the nearest-neighbour strategy, even though the recall of chunks is strictly unnecessary, as all the required information for production is present in front of the participant? Alternatively, is this a case of the processes of chunking interfering with a potentially more efficient strategy, because the propensity of the mind to retrieve known chunks of information cannot be intentionally suspended?

As the participants are using chunks the overall approach to drawing cannot be the nearest neighour line strategy or some other that primarily operates at the level of individual lines. The early dominance of the frame group of patterns suggests that a strategy based on a spatial schema or template (Gobet & Simon, 1996) was being used. The participants draw the frame first, which then provides spatial locations (or slots) as cues for the retrieval of particular chunks. This interpretation is preferable to a strategy in which the order of production of patterns/chunks is in terms of their perceptual salience or memorability. There are other patterns/groups that appear more salient than the frame group, which is relatively diffuse and masked by other patterns.

In the early sessions the transition count data suggests that the patterns/chunks had less of a role: the initial few drawings may have used something akin to the nearest neighbour strategy. Learning is occurring over the sessions in the experiment. What is surprising is how quickly the participants were drawing near perfect versions of the diagram consisting of 13 patterns and 56 lines. The effects of learning are seen in the declines in the pause data (Figure 4) and transition counts for the patterns (Figure 5), and suggested by the transition counts for the groups in the tracing mode (Figure 6). The rapidity may be explained by the likely use of the spatial scheme drawing strategy. The spatial schemas provide a systematic way of organizing the information that does not require production to follow a single rigid sequence of elements that is vulnerable to breaking down as a whole if any one subsequence is forgotten. Further, although the diagram is supposed to be abstract, it is possible that the participants may have impose a meaning on the diagram for themselves (e.g., fish, rocket) and thereby adding semantic information that associates particular patterns to specific locations as part of the schema. It would be interesting in future work to manipulate the presence of the overall spatial schema and the degree of semantic content.

Acknowledgments

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