7
General Discussion

Extant literature is replete with research on feature binding using simultaneous presentation. In contrast, the focus of this research was to study the interaction of presentation modes and locations in feature binding. Simultaneous and sequential modes of presentation of multiple objects were orthogonally manipulated with unchanged and random locations, and were compared using detection of change in binding of color and shape as the task.

Previous studies [e.g., Allen *et al.*, 2006; Brown and Brockmole, 2010] show that usually simultaneous presentation results in better performance than sequential presentation. But simultaneous presentation also implies showing stimuli in multiple locations together and thus allowing participants to encode them in relation to each other. This relational or configural encoding confers a huge advantage to the simultaneously presented stimuli in comparison with sequentially presented stimuli [which are usually presented in the same central location]. This is particularly true for binding as locations are theoretically ascribed a premier role in feature binding [Treisman and Sato, 1990; Wolfe, 1994]. Empirical studies of binding confirm the special role of locations [e.g., Jaswal and Logie, 2011; Logie *et al.*, 2011; Treisman and Zhang, 2006].

To unravel the confound between simultaneous presentation and location information, and to assess the relative importance of locations in both modes of presentation, it was decided to independently manipulate locations and mode of presentation in the same experiment, using a repeated measures design. Experiments 1 to 5 were carried out using this general design with modifications in each experiment to test specific ideas. Then, the same experimental design was implemented in the fMRI environment to determine whether brain activations in predefined ROIs, could substantiate the idea that simultaneous and sequential modes of presentation are affected differently by location information, and in fact, are presumably contingent on different factors. Conjunction null analyses were carried out to assess the areas commonly activated at the different levels of each independent variable.

The results have been discussed in detail in Section 5.5 [Experiments 1-5] and Section 6.4 [the fMRI experiment]. The present chapter builds on these previous sections, and needs to be considered in aggregation with them. In this chapter, the highlights of the results are presented, noting their contrast to, or consonance with, results in previous studies. Then, the implications of behavioral as well as fMRI results for the process of feature binding are discussed, with respect to attention, working memory, and strategy effects.

7.1 THE MAJOR RESULTS

The results of the behavioral studies clearly show that locations are an important factor in simultaneous presentation, significantly enhancing the performance of the participant when they were unchanged, and reducing performance when they were random from study to test.

However, locations did not play a significant role in performance with the sequential mode of presentation. These results are in consonance with previous studies by Jaswal and Logie [2011].

The present research commenced by contrasting two different ways of presenting stimuli one by one, albeit in different experiments. In Experiment 1, stimuli were presented one at a time to build up the study display, whereas in Experiment 2, the previous stimulus vanished as the next one was presented. In each experiment, the direct contrast of sequential presentation was with simultaneously presented stimuli. Also, in both experiments, locations were orthogonally manipulated to be unchanged or random from study to test. Results showed that merely adding a temporal cue, i.e., presenting stimuli one by one to build up the study display, did not lead to a different level of change detection performance as compared to simultaneous presentation. However, when sequential presentation was such that one stimulus vanished as the next was presented, performance was significantly less than in the simultaneous presentation condition. In both experiments, however, locations had a significant effect, with performance being better when locations remained the same, than when they were random from study to test. Collectively these results show that location is a very powerful and prominent cue, and temporal cues are ignored, or become redundant, if the participants can rely on configural encoding, with the help of location information. As the predicted main effects and interaction were clearer in Experiment 2, the rest of the experiments, including the fMRI experiment, were carried out using the same method of sequential presentation, i.e., presenting the next stimulus with the offset of the previous one.

Experiments 3, 4, and 5, further explored the role of encoding factors in the performance of the participants in response to the two modes of presentation. In Experiment 3, the presentation time of the four simultaneously presented stimuli was curtailed to 250 ms to make it equal to the presentation time of *one* stimulus with sequential presentation. But, this had no effect on the performance of the participants. Probably this was because all stimuli in the simultaneous presentation condition had already been encoded even at 250 ms, and were represented in VSTM. Haladjian and Mathy [2015] have shown that about 200 ms is sufficient for participants to encode locations in visuo-spatial memory, analogous to taking a "snapshot".

However, the same may not hold for sequentially presented stimuli. To test the arguments that probably 250 ms each was not enough for the sequentially presented stimuli to be encoded and consolidated, or alternatively, that stimuli were quickly encoded but their representation 'degraded' over 250 ms, in Experiment 4, blank intervals were introduced after each stimulus in the sequential presentation condition. This was done with the idea that the blank intervals after every stimulus would allow the participant to consolidate the memory of the stimulus and/or protect it from being overwritten by the next stimulus, and hence increase the performance of the participants in the sequential presentation condition. The results did show no significant difference between sequential and simultaneous presentation conditions. However, the *ANOVA* comparing Experiments 2 and 4 showed neither a significant main effect of experiments nor any significant interaction effects. A careful comparison of the mean performances in Experiments 2 and 4 (depicted in Figures 4.6 and 5.5 respectively) revealed that performance did not increase in sequential presentation condition. Rather, it *decreased* in the simultaneous presentation condition with unchanged locations, probably because the very long presentation time in this condition [which was 1750 ms to equate it with the total presentation time for sequentially presented stimuli] led to forgetting. Earlier, Ricker and Cowan [2014] had used blank intervals in their experiment with unifeature stimuli to yield better performance with sequential presentation. However, there was no such effect on performance in the sequential presentation conditions in the present work. Ricker and Cowan [2014] had tested memory for unfamiliar shapes, whereas the present experiment was testing feature bindings. The inference is that presumably, feature bindings are already represented in the VSTM beyond

iconic memory, and hence do not benefit from the opportunity of consolidation [or protection] given by blank intervals.

The idea that feature bindings are represented in VSTM beyond the iconic store, was substantiated by Experiment 5, where pattern masks comprising visual noise were used in a bid to disrupt performance. However, there were no significant differences in the performance of the participants as compared to Experiment 2, substantiating that feature bindings were already represented and maintained in visual memory, beyond iconic storage. As such, they are immune to masks in line with several studies [e.g., Phillips, 1974; Sligte *et al.,* 2008; Smithson and Mollon, 2006], and presumably only affected by factors which organize information after basic perceptual processing.

In all these experiments [Experiments 2, 3, 4, and 5], the interaction effect was always obtained, clearly showing that locations were a factor only with simultaneous presentation, but not sequential presentation. The results are in consonance with several earlier theories [Schneegans and Bays, 2017; Treisman and Sato, 1990; Wolfe, 1994] and empirical studies [Hollingworth, 2007; Logie *et al.*, 2011; Richard *et al.*, 2008; Treisman and Zhang, 2006; Udale *et al.*, 2017] showing the importance of locations in feature binding in visual working memory.

Particularly, the results are consistent with the three separate studies reported by Jaswal and Logie [2011] who inferred that configural encoding due to locations was an important factor in the performance of participants. In their work, in the experiment when stimuli were sequentially presented such that one stimulus vanished as the next appeared, performance was barely above chance, and much lower than the other two experiments which allowed participants to rely on location information to encode stimuli in relation to each other. The present research augments these earlier data, with a direct comparison of simultaneous and sequential presentation and establishes locations as a factor in simultaneous presentation alone [besides identifying the brain regions associated with these results].

The present experiments have also directly contrasted the relative importance of location and temporal cues in feature binding, to show that, if available and relevant, the performance of participants relies on the location cue. This is not to say that the temporal cue is not used at all. In fact, all experiments except Experiment 1, have shown serial position effects in the sequential presentation conditions, with both primacy and recency effects being quite clear. This indicates that serial positions influence the performance of the participants in this condition. However, when location information that allows configural encoding is present [Experiment 1], the serial position effects are not observed in the sequential presentation conditions, indicating that the participants do not rely on the temporal cue, if and when the spatial cue is present and relevant.

The fMRI study was more revealing regarding the factors differentially affecting performance in these two modes of presentation. After collecting fMRI data in all the four experimental conditions, and obtaining the relevant contrasts from the baseline, conjunction null analyses were carried out to assess the brain areas activated commonly at the different levels of the two independent variables. Results showed that brain activation was much more in intensity and extent with the sequential mode of presentation, and with random locations. The simultaneous mode of presentation, and unchanged locations, recruited exactly the same brain areas in the parietal cortex and the insula, confirming that when presented with many stimuli simultaneously, participants almost automatically encode them in terms of their locations. Conjunction null analysis for random locations showed largest activations in terms of intensity as well as extent, ranging from the occipital to the frontal areas. Conjunction null analysis for sequential presentation, also showed activation in several areas. The inferior temporal gyrus was uniquely active with sequential presentation, indicating a role for object based processing in the sequential mode of presentation.

Differential levels of activation in all four conditions were compared by searching specific ROIs defined on the basis of previous studies to be important in feature binding. Significant results were obtained in eight out of the ten ROIs searched. The main effect of locations as well as its interaction with mode of presentation was significant in the bilateral intra parietal sulci, bilateral superior parietal regions, and the right fusiform area. The left precentral gyrus, showed only a significant interaction effect. In addition, the main effect of location was significant in the right superior parietal cortex around the coordinates [15, -62, 63] defined on the basis of Shafritz *et al.* [2002]. However, the interaction effect was not significant in this case.

This last result regarding the right superior parietal cortex is noteworthy because Shafritz *et al.* [2002] had reported significant activation at these coordinates with simultaneous presentation when they tested memory for bindings rather than unifeature objects, but no clear results for sequential presentation. They had inferred that "the parietal cortex is involved in feature binding but only when spatial information is available to resolve ambiguities about the relationships between object features" [Shafritz *et al.*, 2002, p. 10917]. However, they had not independently manipulated locations. In their experiment, the simultaneous presentation [of two stimuli] was above and below fixation, whereas sequential presentation was at the center of the screen. Thus, mode of presentation was confounded with location information. The present research attempted to unravel this confound and found that in the ROI around these coordinates, only location was a factor in performance. Neither the main effect of mode of presentation, nor its interaction with locations was significant in the right superior parietal cortex. This clearly allows the inference that location and not mode of presentation was the crucial factor leading to better performance in memory for color-shape binding rather than for unifeature objects in the experiment by Shafritz *et al.* [2002].

To encapsulate the results, behavioral data from Experiments 2, 3, and 4, which were similar to the fMRI experiment, showed best change detection performance in the unchanged locations condition with simultaneous presentation as compared to the other three conditions. Brain activation studied through fMRI showed least activation in the unchanged locations condition with simultaneous presentation and maximum activation in the random locations condition with simultaneous presentation, and no differences between the two location conditions with sequential presentation.

This pattern of results clearly suggests that location is a factor in simultaneous presentation but not sequential presentation. It is the present researcher's contention that the superior performance of the participants in this condition is due to configural/ relational encoding of stimuli in a spatiotopic pattern when seen simultaneously in the study display. In the unchanged locations condition, this pattern aids detection of changes because the test stimuli occur in the same pattern. In the random locations condition, the test display does not match the encoded pattern, and hence performance decreases. In the sequential presentation condition this configural representation is difficult to build, and hence performance is unaffected by locations being unchanged or random. Locations are simply not a factor in sequential presentation, and one must search elsewhere to explain the performance of the participants with sequential presentation.

At this juncture, it is important to note the consonance of the present results with the emerging research and theorizing by the Computational Cognition Group at the University of Cambridge led by Bays. Although, the neural model by Schneegans and Bays [2017] indicated the crucial role of location in binding other non-spatial features as well, this was only for simultaneously presented stimuli. They did not address the question of sequentially presented stimuli. More recent work by Harrison and Bays [2018] has shown the lack of spatial interactions between sequentially presented stimuli. They speculate that with sequential presentation, non-spatial features may be linked through the temporal order of stimuli, or they may be linked directly to each other. In both cases, there may be an involvement of the parietal

or frontal areas. Certainly, the precision of the memory of their participants was unrelated to cortical spacing in the early visual areas. These inferences match the present researcher's contention that locations are not a factor in performance with sequentially presented stimuli.

7.2 IMPLICATIONS OF THE RESULTS FOR THE PROCESS OF FEATURE BINDING

The present researcher believes that combining the results from the behavioral and fMRI experiment can enhance the understanding of cognitive as well as neural mechanisms underlying these results. The differential analyses in specific ROIs revealed lesser activation in in the parietal regions, the precentral gyrus, and the fusiform areas, in the simultaneous presentation condition with unchanged locations, suggesting that the superior behavioral performance in this condition does not rely on object-related shifting focus of attention. The relatively greater activation in the parietal areas, precentral gyrus, and fusiform areas in the two sequential conditions as well as in the simultaneous presentation condition with random locations suggests that visual search and object focused attention play a significant role in these conditions. Evidence from the previous literature shows that shifting the focus of attention causes activation in the parietal as well as precentral areas of the brain during visual perception [Corbetta, 1998; Corbetta and Shulman, 1998; Grosbras *et al.*, 2005]. The fusiform area is well-established as the area for object recognition [Grill-Spector *et al.*, 2001].

The role of attention in visual feature binding is well established [Treisman, 1998]. The feature integration theory advocates that attention works as a 'glue' which helps to bind together different features to the spatial map that exists in the brain [Treisman and Gelade, 1980, Treisman and Sato, 1990]. If that 'glue' becomes weaker, features are free to flow, and form illusory conjunctions [misbindings]. The performance in the simultaneous presentation condition with unchanged locations probably relies on finding changes in a relational or configural representation of the stimuli in the study display and a matching test display, requiring lesser oculomotor responses as well as shifts in the focus of attention in comparison with the other three conditions. The shifts in focus of attention are probably more in the random locations condition as the participant searches for swapped stimuli in the test display, and even more in the sequential presentation as the participant focuses on each successive stimulus presented in different locations in the study phase itself. Indeed, one may infer that whereas the performance in the simultaneous presentation condition with unchanged locations relies on spatial attention, the other three experimental conditions recruit object-focused attention. The brain areas, which emerged significant in conjunction analyses, also substantiate this inference. For example, the inferior temporal gyrus, associated with object based processing in several studies [e.g., Grill-Spector *et al.*, 2001] was active only in the sequential mode of presentation.

Another plausible account of increased activation in the condition with simultaneous presentation and random locations, and the two sequential presentation conditions in the ROI analyses is the increase in utilization of working memory resources in these conditions. In the condition with simultaneous presentation and random locations, the participant has to search for swapped color-shape binding among stimuli presented in changed locations, and this has to be done with reference to the spatiotopic representation of the study display. So participants are maintaining a template [of the study display] in their memory and processing the stimuli in front of them in the test display one by one at the same time. During sequential presentation, during the study display itself, participants need to, at least, maintain the information of previous stimuli as the next is encoded, if not to integrate them into a whole sequence. As the stimuli increase one by one, this would become more difficult as well. Thus, participants are always doing two things at the same time in the sequential presentation condition even as the study display is being presented, what to speak of the subsequent processing of the test display. This implies increased and intensive requirement of working memory resources for dual tasking in the condition with randomized locations and simultaneous presentation, as well as the two

sequential presentation conditions. Increased activation in frontal and parietal areas in these dual task conditions, as found in the present study, has been reported by several previous studies [e.g., Herath *et al.*, 2001; Schubert and Szameitat, 2003]. Increased activation in tasks with increasing set size has also been reported. Cohen *et al.* [1997] studied brain activations using an n-back task with sequences of letters. WM load was increased from 0-back to 3-back conditions. Brain areas related to load were dorsolateral prefrontal cortex, more posterior and inferior regions of frontal cortex, and posterior parietal cortex. Silk *et al.* [2010] found that the right post central gyrus shows higher activation with increasing set size in a spatial working memory task involving recall of locations presented simultaneously.

Another possible explanation of the results may be the different strategies adopted by the participants in the different experimental conditions. Strategic influences in feature binding in visual working memory have been emphasized by some recent studies [Atkinson *et al.*, 2018; Udale *et al.*, 2018b], which essentially argue that participants tend to use the most optimal strategy in the given scenario. In the present experiments, participants may be using configural encoding in the simultaneous presentation condition with unchanged locations, simply storing the study display until the test display is shown and then comparing the two configurations so that the changed stimuli simply 'pop out'. Jiang and Kumar [2004] and Jiang *et al.* [2005] have suggested such a 'store and compare' process for patterns presented one after the other. In the other three conditions, however, participants need to focus on each stimulus. Configural encoding is of no help, and in fact, may actually lower performance when locations are random from study to test. An object-focused strategy, which retains the binding of each stimulus in working memory, is perhaps the best way to achieve success. Whatever little help is given by the successive presentation of stimuli is used [as shown by the serial position effects of primacy as well as recency]. Nevertheless, the temporal cue is weak and does not allow a strong enough representation for as good a behavioral performance as the location cue in the unchanged locations condition with simultaneous presentation. So the participants recruit extra focused attention as well as working memory resources for performance in this condition.

These accounts are not mutually exclusive and fit well with the contention that locations play a role only in the simultaneous presentation condition. In the simultaneous presentation condition, the spatiotopic representation increases performance in the unchanged locations condition and decreases it in the random locations condition. In the sequential presentation condition, despite recruiting extra attentional resources, it is difficult to build a clear representation of the stimuli together, and location has little role to play in the performance of the participants.

7.3 CONCLUSION

The present research explored the differences in behavioral data and brain activation due to simultaneous and sequential modes of presentation, with locations being unchanged and random in a change detection task testing color- shape binding. Behavioral data confirmed that spatial locations and consequent configural encoding of multiple stimuli is one of the major reasons for increased binding performance with simultaneous presentation. When locations are random from study to test, the spatiotopic representation of the study-display mismatches the test display, and as a result, binding performance is significantly reduced. The pattern of brain activation reveals lowest activity in the simultaneous presentation condition with unchanged locations. Perhaps this is because encoding as well as retrieval is easy in the configuration-preserved display. In all other three conditions, encoding, or retrieval, or both, are probably difficult due to lack of links between the stimuli. Thus, these conditions show more activation in the brain. This may be because these conditions recruit greater object focused attention, or WM resources, or different strategies. Future studies specifically designed for these purposes might reveal the exact role and relations among these factors.