Feature Binding in Working Memory

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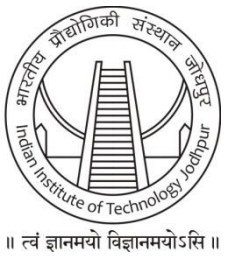

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Summary and Conclusion

The stimuli in the world vary along different dimensions such as color, shape, texture, orientation, location, movement, etc. The unique combination of these features makes a stimulus distinct, from not only the background, but also, the other stimuli. These features are processed in diverse areas of the brain. The process of combining different visual features such as color, shape, size, location, movement, etc., to form an integrated object representation for further processing, is visual feature binding.

The primary motive of the present research was to compare simultaneous and sequential modes of presentation of stimuli in the process of binding. The confound of spatial configuration and simultaneous presentation was noted in the review of literature. In order to disentangle locations and mode of presentation, these two variables were manipulated orthogonally to create four experimental conditions, viz., simultaneous presentation with unchanged locations, simultaneous presentation with random locations, sequential presentation with unchanged locations, and sequential presentation with random locations. Binding of color and shape was to be tested in these four conditions.

The main expectation was that the difference in binding performance due to unchanged and random locations would be much more in the simultaneous presentation condition than the sequential presentation condition. The interaction was tested in behavioral experiments and also at the neural level through fMRI in specific regions of interest defined on the basis of previous studies of feature binding. Conjunction analyses of fMRI data revealed the areas of activation in the different levels of each independent variable.

8.1 RECAPITULATING THE PRESENT RESEARCH

The primary aim of the present research being to assess the separate and interactive effect of modes of presentation and locations on feature binding, at the behavioral as well as neural levels, a change detection task was used to assess feature binding. In this task, which one may call 'swap detection', the participant needs to detect whether the combination of features of the stimuli has changed from study to test display. As participants are presented with exactly the same features in the study and the test display, the participant cannot do this task by remembering single features alone. This task lends itself not only for testing binding at the behavioral level, but also the neural level.

Both the independent variables had two levels: presentation mode was either simultaneous or sequential, and locations were either unchanged or random from study to test. Simultaneous presentation implied that all four stimuli were presented together in any four locations within an invisible 3×4 grid. In sequential presentation, the stimuli appeared one by

one in any four locations within an invisible 3×4 grid. In unchanged locations condition, the location coordinates of stimuli were exactly the same in the study and test displays, whereas in the random locations condition, the location coordinates of stimuli were random [with replacement] from study to test display. The two independent variables were fully crossed to produce four experimental conditions.

After having familiarized the participants with each condition, color- shape binding was tested by randomly presenting a binding change on half the trials and no binding change on the other half of the trials. The performance of the participants was recorded, and transformed into d primes in each condition, for each individual participant. The statistical analysis of behavioral data was carried out using the frequentist approach, but was supported by the Bayesian approach to test the hypotheses. In general, an interaction effect was expected in all experiments, as randomizing locations or keeping them unchanged from study to test was assumed to result in a greater difference in the performance of the participants when stimuli were simultaneously presented than when they were sequentially presented. Using the same independent variables, an experiment was also conducted in the fMRI environment to study the areas of activation and the activation levels associated with the different levels of the independent variables. The five behavioral experiments and one fMRI experiment conducted in the present research are summarized in the following paragraphs.

In Experiment 1, a version of sequential presentation was used where previous stimuli remained on screen when the next stimulus appeared, so that gradually the whole display was built up. This kind of sequential presentation was expected to not only preserve the relative location information among stimuli, but also provide an additional temporal cue. The results from this experiment did not show a significant difference between the two modes of presentation. Performance was better with unchanged than random locations, but the interaction of mode of presentation and location was also not significant. Further, serial position effects were not observed in the sequential mode of presentation. Thus, it was inferred that if location information is present and relevant, participants use that information. The additional temporal signal has no benefit [or cost either].

Experiment 2 was identical to Experiment 1, except that the stimuli in the sequential presentation mode were shown so that the previous stimulus was no longer present when the next one appeared. This change meant that participants could not encode the stimuli according to their relative locations in space. Thus relative location information was removed from sequential presentation. The results from Experiment 2 showed a significant difference between simultaneous and sequential presentation, between unchanged and random locations, and a significant interaction of modes of presentation and locations. A larger difference was seen between unchanged and random locations with simultaneous presentation than with sequential presentation. It was clear from this experiment that location was a factor in the effect of simultaneous presentation, but not in the effect of sequential presentation.

The only difference between Experiments 1 and 2 was the type of sequential presentation. In Experiment 1, stimuli were presented one by one so that the study display was gradually built up, but in Experiment 2, stimuli were presented so that the onset of a stimulus coincided with the offset of the previous one. Mode of presentation did not have a significant effect in Experiment 1. However, in Experiment 2, there was a clear difference in the performance of the participants due to mode of presentation. An interaction between mode of presentation and locations was also observed. In both experiments, the participants could have used the temporal signal to encode the stimuli, but in Experiment 1, they could also encode the stimuli as a spatial pattern. It is clear from comparing these two experiments, that this configural encoding is what the participants do. The serial position effects are also evident only in Experiment 2, but not in Experiment 1. Thus, it can be inferred that participants use a temporal cue only when the more powerful location cue is weak or absent.

In Chapter 5, three behavioral experiments are reported. All of them used the sequential mode of presentation in which a new stimulus was shown as the previous one vanished, as it was this kind of presentation in Experiment 2, which had shown significant effects. All the three experiments were designed to change one variable at a time in the encoding process. In Experiment 3, the total time of presentation of the study display in the simultaneous presentation condition was reduced to 250 ms to make it equal to the presentation time of one stimulus in the sequential presentation condition. The idea was to test whether the better performance in Experiment 2 with simultaneous presentation was merely because participants could view the simultaneously presented stimuli for the longer duration of 1000 ms, whereas each stimulus in the sequential presentation condition could be viewed for 250 ms only. The results of Experiment 3 showed a significant difference between presentation modes, with higher performance with simultaneous than sequential presentation. Indeed, a three way *ANOVA* comparing Experiment 2 and 3 showed neither a significant main effect of experiments, not a significant three-way interaction, showing that the pattern of results in Experiments 2 and 3 was exactly the same.

With the idea that it was the sequential presentation condition, in which the stimuli [and performance] suffered due to a short presentation time per stimulus, in Experiment 4, a blank interval followed each stimulus in the sequential presentation condition. Continuous presentation of stimuli may not provide enough time for consolidation of each stimulus. Further, a subsequent stimulus can overwrite a previous stimulus. It was presumed that blank intervals after each stimulus would allow time for consolidation of the representation of the stimulus, and/or protect it from dissipation, thus increasing binding performance in this condition. Results showed that the main effect of presentation was not significant. However, a comparison of the results with Experiment 2 and a careful consideration of data revealed that the performance had not been enhanced in the sequential presentation conditions; rather, it had decreased in the simultaneous presentation condition with unchanged locations. In a bid to make the exposure duration of stimuli equal in both conditions, the study display was presented for 1750 ms in the simultaneous condition. Thus, it was inferred that the lack of difference between simultaneous and sequential presentation in this experiment was driven by lesser performance in the simultaneous presentation condition with unchanged locations, due to the overly long 1750 ms presentation time. This duration might have made it difficult to maintain the representation in working memory, or induced boredom and/or fatigue among the participants. The main effect of locations and the interaction between the two independent variables were, nevertheless, significant in this experiment also.

In Experiment 5, a mask was used immediately after the study display to eradicate the effect of iconic memory from the performance of the participants. Otherwise, the experiment was the same as Experiment 2. Results followed the same pattern as observed in Experiment 2. Even the performance in the simultaneous presentation unchanged locations condition was unaffected by the mask. These results were possible only if the stimuli were already represented in VSTM, which is apparently immune to masking [Phillips, 1974; Smithson and Mollon, 2006]. The higher performance in the simultaneous presentation condition was not due to iconic memory, rather configural encoding of stimuli according to relative locations makes the representations quite durable and easily preserved during the maintenance phase in working memory. The results of all behavioral experiments together suggested that the location information produces 'vulcanized' representations in working memory, which are strong as well as flexible, and are not easily overpowered by subsequent stimuli.

Further the fMRI procedure was opted to assess the neural correlates of binding within simultaneous and sequential presentation. The fMRI experiment was the same as Experiment 3, with a few changes necessitated by the fMRI environment [highlighted in Chapter 6]. A block design was used to create the experiment for fMRI. Fixation and response time window were

kept constant in each trial to create a fixed sequence protocol. The total number of trials in each experimental condition was halved to prevent fatigue in the scanner. Also, articulatory suppression was not used.

Two kinds of analyses were performed with fMRI data. Brain activation in the four experimental conditions was contrasted to test if the interaction of locations and mode of presentation was shown at brain level in the ROI indicated by previous research to be important in feature binding. In addition, conjunction null analyses were carried out to assess the areas commonly activated in the different levels of each independent variable.

Seven out of ten areas studied in ROI analyses showed a significant interaction. They were in the bilateral parietal region, left precentral gyrus, and the right fusiform areas. Whereas behavioral response was the maximum in the condition with simultaneous presentation and unchanged locations, the neural response was the minimum. This is understandable, as ease and efficiency of behavioral performance is associated with lesser activation in the brain. It is inferred that it is only in the simultaneous presentation condition with unchanged locations that the participants almost automatically encode the stimuli in the study display in relation to each other, and simply note the change in the pattern of the test display. In all other experimental conditions, there is a requirement for shifts in the focus of attention. In the simultaneous presentation condition with random locations, participants need to literally search for the stimulus, which has changed in binding from among the changed pattern presented in the test display. In the sequential presentation condition, they need to shift their focus to each stimulus as it is presented in a new location one after the other in the study display itself, whether the locations are unchanged or random in the test display. Thus, greater activation in terms of intensity as well as extent was observed in each of the three remaining experimental conditions, in all the ROIs.

The results from the conjunction analyses support the contention that sequential presentation as compared to simultaneous presentation requires more brain resources as it shows greater intensity and extent of activation. Besides activation of the frontal and parietal lobes, it is interesting to note that this is the only case, which shows activation in the right inferior temporal gyrus, signifying the requirement of memory. Participants are likely storing a stimulus and processing the next one at the same time with sequential presentation, hence the activation in this memory related area.

Conjunction analyses also revealed that random locations is associated with activation in the largest clusters in this experiment. The activation manifests the requirement for shifts in attentional focus as well as object-focused attention with random locations, with many areas in the occipital lobe showing activation, besides the parietal and frontal areas.

Perhaps the most interesting result of the conjunction analyses was that unchanged locations and simultaneous presentation recruited exactly the same areas of the brain. This is in consonance with the idea that whenever participants are presented with several stimuli at the same time, they almost automatically store and process them in relation to each other. Given that there is a spatial map in the visual system, this is not surprising, for a template already exists in the brain to process the incoming stimuli.

However, when stimuli are presented sequentially, location information is not relevant for feature binding performance. Probably, other factors are more important in this kind of presentation. The serial position effects were observed in all behavioral experiments, illustrating that the temporal code is relied on whenever it is present. Whether serial positions are used instead of locations to bind other surface features, or whether surface features are directly bound to each other in the mental representation [as questioned by Harrison and Bays, 2018] can only be ascertained with future research in this area.

Nevertheless, the greater importance of location cues as compared to the temporal cues in feature binding is clear from these experiments. Together, the results from the behavioral and fMRI data yield the conclusion that location information acts to 'vulcanize' the representation of objects to make them strong, durable, and resistant to overwriting by subsequent stimuli. Thus behavioral performance is best with simultaneous presentation and unchanged locations. When stimuli are presented sequentially, binding can happen only with more intensive use of brain resources. This may be due to the use of object-based attention, as the inferior temporal gyrus, associated with object based processing in many previous studies [e.g., Grill-Spector *et al.*, 2001] was activated only in the sequential mode of presentation. Alternatively, it could be due to intensive use of working memory resources, as the fronto-parietal areas associated with working memory [e.g., Li et al, 2017; Palva *et al.*, 2010; Silk et al, 2010] were also more activated with sequential presentation . It is also possible that participants were using whichever strategy they considered was the most efficient to secure good performance in the different experimental conditions. Recent studies have demonstrated WM capacity based strategy effects in feature binding [Atkinson *et al.,* 2018] as well as that participants can switch between spatial and non-spatial strategies depending on task demands and individual differences [Udale *et al.,* 2018b]. Future research studies aimed at these specific explanations are clearly requisite.

8.2 SPECIFIC CONTRIBUTIONS OF THE PRESENT WORK

The present research has made the following specific contributions:

1. The present research has clarified the confound of simultaneous presentation and relative locations as factors in feature binding that existed in literature. Specifically, the conclusion of Shafritz *et al.* [2002] that feature binding requires simultaneous presentation of several stimuli at different locations, can be modulated. This conclusion was based on activation in the parietal cortex observed in their experiment which did not adequately control for locations. As the present researcher completely crossed mode of presentation and locations, differential activation in the same coordinates as Shafritz *et al.,* [2002] clearly demonstrated that locations rather than modes of presentation are the critical factor that affect feature binding.
2. The present experiments augment the results of Jaswal and Logie [2011], who had also crossed random and unchanged locations with the two modes of presentation, but in different experiments. The present experiments directly compared simultaneous and sequential presentation in the same experiments, and thus unequivocally showed that locations have an important role to play only in the simultaneous mode of presentation. Further, by carrying out the experiment in the fMRI scanner, the present researcher demonstrated the areas of the brain involved in the different levels of the two independent variables, and the differential involvement of brain areas in specific ROIs in the different experimental conditions.
3. Serial position effects in the performance of the participants in the sequential presentation conditions show that temporal cues inherent in serial positions can be used for feature binding, although the spatial cues dominate if they are also present.
4. The results of conjunction analyses for different levels of the two independent variables demonstrated the involvement of only the parietal cortex and insula with simultaneous presentation and with unchanged locations. However, several other brain areas in the frontal and parietal lobes were additionally activated with sequential presentation, the most notable being the object processing area of the inferior temporal gyrus which was uniquely activated with sequential presentation, attesting to the role of object memory in sequential presentation. The greatest levels of activation in terms of extent as well as intensity were observed with random locations, with the occipital areas associated with visual search being activated in addition to frontal and parietal areas.

The present research also indicates that different types of feature binding may exist, depending on the kind of features involved. At the very least, binding with and without locations involves different brain areas and psychological processes. These differences must be further explored, and their correlates established, if one ever hopes to apply this knowledge in practice. Independent, efficient, and low cost cognitive tasks and tests could be prepared for different types of neurodegenerative diseases or brain disorders. In the domain of artificial intelligence, these results may be considered in object recognition problems in computer vision algorithms. Thus, this research may contribute to theoretical knowledge in feature binding as well as practical concerns.

8.3 FUTURE POSSIBILITIES

Every research has limitations often attributable to the choices made by the researchers. Hopefully, the limitations can be overcome with future studies. The primary limitation of the behavioral studies in this series of experiments is that only some of the encoding factors could be manipulated and studied. Whether and how other important factors, such as strategic processing or individual differences [as espoused by Atkinson *et al.*, 2018; Udale *et al.*, 2018b], affect feature binding remains to be seen. Another limitation of current research is that it does not provide the exact neural correlates for the dynamic nature of feature binding. It showed the response pattern of binding specific regions. But how these regions come together and contribute in the binding process needs investigation, probably using other techniques with better temporal resolution. Such attempts are currently being made in several other studies, albeit with different paradigms [e.g., Li et al, 2017; Zamboni et al., 2020]

Nevertheless, the present research successfully decoded the link between location and mode of presentation in behavioral as well as neural responses. These results add to the theorizing and experimental work on the processing of the two presentation modes in the visual modality. The results also indicate the analysis of serial position effects as an important way to assess feature bindings of sequentially presented stimuli. Extant literature [e.g., Shimi and Logie, 2019] shows that feature bindings are extremely short lived and fragile, yet have an influence over the long term, and can themselves be influenced by long term knowledge. Presumably, serial position analyses can be a pathway to understand how bindings function over time.

The fMRI responses could be used in network analysis to model the contributing regions in binding. This can suggest the possible structural, functional, and effective connectivity during the binding process. The difference in network models for simultaneous and sequential presentation can be assessed by using the obtained fMRI responses from the present research itself, and is the focus of continuing work by the researcher. Network analyses can clarify the picture of the binding process in the brain, and can also study the interaction of brain regions responsible for binding, with those contributing to other cognitive processes, such as reasoning, problem solving, or the construction of self.

8.4 CONCLUSION

Overall, the present research has successfully broken the link of location information and simultaneous presentation during the binding process and compared simultaneous and sequential presentation. It is clear that simultaneous presentation is better only if the relative location information is preserved. Feature binding itself is revealed as a multi-step and resource demanding process, particularly if location cues are absent and/or when the stimuli are presented sequentially.