1

Introduction

The human brain is a network of neurons, which function by electrochemical means to process information, finally yielding a response as output. Analogous to an electrical circuit, there are various pathways underlying different functions with several neurons firing in specific ways to complete a sub-process. A primary task for this system is the input of relevant information. Like a prism, the brain breaks down the signal received from stimuli and sends the information to different areas. Thus, there is a need for a mechanism to integrate these bits scattered all over the brain, so that further processing can happen.

Feature binding is the process that combines information from diverse areas of the brain. It is basic to information processing in the brain, and is important to several other cognitive functions, some arguably more important than binding itself. Von der Malsburg [1999] proposed it to be essential for parallel processing of myriad objects in the environment. Fodor and Pylyshyn [1988] insisted it to be crucial for production of language. Crick and Koch [1990] held it to be the neural correlate of consciousness [although they later retracted this idea]. Certainly, objects which result as a process of feature binding are widely accepted as the basic building blocks of information processing, enabling higher processes such as memory [Halford *et al.*, 2007], subjective time frames [Poppel, 1997], and creation of the phenomenal self [Metzinger, 1995]. The importance of feature binding extends to non-human intelligent systems as well, such as those with machine learning, which function on the basis of feature detection and pattern perception [Alexandropoulos *et al.*, 2019]

Binding implies dealing with the myriad stimuli impinging on the sensory system at any given time. Efficient processing demands that the system is able to distinguish the signal from background noise and differentiate between multiple objects. Both these, identification and discrimination, are greatly aided by the separation of objects in space or time. Spatial distribution of objects implies simultaneous presentation whereas temporal distribution means sequential presentation. In everyday life, both types of presentation modes are encountered. However, when it comes to research, most of the binding studies were initially done with simultaneous presentation of the stimuli, using the change detection task. In this task, two displays are presented, each with a set of stimuli. The participant has to detect whether any of the stimuli in the test display have changed in comparison to the study display. Simultaneous presentation of all stimuli in the study display encourages the encoding of relative location information, which is an important cue for binding.

The importance of location in binding has been emphasized by the feature integration theory [Treisman and Gelade, 1980; Treisman and Sato, 1990] as well as the guided search model [Wolfe, 1994].The feature integration theory [Treisman and Gelade, 1980] suggested that binding is mediated by spatial attention that links separate features to a common location. Treisman and Sato [1990] held that a "master map" of locations exists in the brain. Attention selects all the features associated with a particular location, and works as glue to bind together those features. Neuroscientists have found evidence for such a master map. O'Keefe and Nadel

[1978] found the existence of place cells in the hippocampus. Hartley *et al.* [2007] also supported the role of hippocampus in topographical processing in short term memory. Jacobs *et al.* [2013] did single cell recordings from patients of epilepsy, which indicated grid cells in the entorhinal cortex and place cells in the hippocampal region. Koen *et al.* [2017] showed that the hippocampus plays a critical role in forming and maintaining complex bindings. Several studies [reviewed in Xu, 2017] have also shown that activity in the retinotopically organized sub regions of the visual and parietal cortex is critical for visual short term memory [VSTM] storage. Schneegans and Bays [2017] proposed a neural model for feature binding in visual working memory based on their empirical work showing that non-spatial features too are bound only through shared locations. Fang *et al.* [2019] demonstrated that when a location is attended, the surround is suppressed, and this sensory mechanism may make locations special.

Behavioral studies also show that location is a special feature, and is remembered better than colors [Wheeler and Treisman, 2002]. Studies also show that bindings are more vulnerable to location change and suggest that location plays a central role in early maintenance and retrieval of bound objects [Hollingworth, 2007; Logie *et al.*, 2011; Richard *et al.*, 2008; Treisman and Zhang, 2006]. Recently, Udale *et al.* [2017] clearly demonstrated that stimuli are encoded only in relation to other relevant stimuli. The background, or irrelevant, non-target stimuli do not participate in this relational encoding. Perhaps, it is for this reason that location emerged as a factor in binding only when a whole display probe was used, but not when a single probe was used in their studies, echoing similar results in Treisman and Zhang [2006].

No wonder then, that simultaneous presentation of multiple objects was considered crucial for binding by many researchers [e.g., Duncan, 1980; Shafritz *et al.* 2002; Treisman and Sato, 1990]. These views have been critically analysed in Chapter 2 in various sections of the review of literature. To briefly foreshadow these ideas, Duncan [1980] proposed that simultaneous presentation allowed competition between various objects and the emergence of biased attention which operated to select only those objects for further processing, which matched the templates in working memory [WM]. Treisman and Sato [1990] proposed a master map of locations in the brain which represented the many simultaneously present objects in the external world, ready for selection by the focus of attention. Presumably, both these reasons [object focused attention and encoding of relative locations], and functional magnetic resonance imaging [fMRI] evidence from their own study, led Shafritz *et al.* [2002] to infer that binding happens only with simultaneously presented stimuli.

However, more recently, researchers have contrasted the simultaneous and sequential modes of presentation in feature binding. Allen *et al.* [2006] compared the two modes of presentation, used a shape-color binding task. Results found less accurate performance with the sequential mode of presentation. Brown and Brockmole [2010] tested binding deficits in older and younger people using simultaneous and sequential modes of presentation. Although the results did not show any effect of age, binding performance was significantly better for simultaneous presentation than sequential presentation. Brown *et al.* [2017] used a similar task, but with single probes, and found better results for simultaneous than sequential presentation for binding as compared to single feature conditions, but only for younger adults in the age range 18 to 25. Gorgoraptis *et al.* [2011] used a memory precision task testing the binding of color and orientation, to compare simultaneous and sequential presentation in the same experiment. The study display presented several colored bars with different orientations. In the test display, a single colored bar was presented as a probe. Participants had to adjust its orientation to match the orientation of the stimulus in the initial display. The test probe was always at center screen. Sequential presentation resulted in low memory precision and more misbindings.

In contrast, other research groups have shown that sequential presentation is better than simultaneous presentation. Yamamoto and Shelton [2009] used real life scenarios and found that

sequential presentation of objects made it easy to memorize them. They used a room layout and six different objects. Participants were shown these objects either simultaneously for 30 secs or sequentially for 2.5 secs per object, with the whole array being shown twice. Results showed better performance with sequential presentation. The confusion generated by many stimuli presented together might also be a factor in the better or equivalent performance, sometimes obtained with sequential presentation, especially in real life conditions, where experience or familiarity with stimuli might mitigate the effects of competition and increase the distinctiveness of stimuli. Emrich and Ferber [2012] also reported that binding errors [location and color] from within the memory set are more common in simultaneous presentation, as it increases competition, than when stimuli are presented sequentially. Ahmad *et al.* [2017] found that competition exists not only in simultaneous presentation, but also when the second stimulus immediately followed the first. Nevertheless, a gap of 500 ms between two stimuli eradicated the effect of competition. Thus, conflicting results for the two different modes of presentation are, at times, observed in literature. Nevertheless, the evidence generally shows that simultaneous presentation yields better performance, particularly in experimental tasks. Perhaps this is because it allows configural encoding. Stimuli can be encoded and remembered in relation to each other and form a pattern more easily when presented simultaneously than when presented sequentially. Given the immense importance of locations in binding, if one really wishes to compare simultaneous presentation with sequential presentation in visual feature binding, location needs to be controlled.

To unravel the effects of mode of presentation and relative locations, it seems imperative to manipulate these two variables independently. Notice that none of the above-mentioned studies focused on the role of locations in simultaneous presentation. In many of these studies, the stimuli were presented at fixed locations for study as well as test, or a single probe was presented as the test at the center of the screen. However, because other features may be addressed through locations [Schneegans and Bays, 2017; Treisman and Sato, 1990; Wolfe, 1994], presenting stimuli at unchanged locations or using a single probe at center screen is not an adequate control. The huge literature on classical conditioning since Rescorla [1967] shows that, to break an association, it is important that the elements participating in the link are presented in a random manner. This suggests that to make locations really redundant/ irrelevant to the stimulus, the best strategy is to make them random from study to test.

Thus, the present research compares simultaneous and sequential presentation when stimuli are presented in unchanged locations and when they are presented in random locations. This work is based on, and augments, previous work by Jaswal and Logie [2011]. They too manipulated locations to be unchanged and random from study to test, using a swap detection task, to study color-shape binding. In separate experiments, Jaswal and Logie [2011] also studied simultaneous and sequential modes of presentation. In their work, Experiments 2, 3, and 4 are relevant to the present research. In all these experiments, locations were manipulated to be either unchanged or random from study to test in a change detection task requiring color-shape binding. In Experiment 2, with simultaneous presentation, performance was significantly better with unchanged locations than in the random locations condition. In Experiment 3, with sequential presentation, in which the study display was gradually built up, performance decreased somewhat in the unchanged locations condition, and the gap between unchanged and random location conditions was reduced. In Experiment 4, with sequential presentation, in which the previous stimulus vanished as the next was presented such that the participants never saw all the stimuli together in the test display, performance was very less, even when locations of the stimuli remained unchanged. Indeed, there was no difference in the performance of the participants in any of the experimental conditions. Jaswal and Logie [2011] attributed these differences to configural encoding of stimuli which is maximum with simultaneous presentation in Experiment 2, somewhat reduced in Experiment 3 where configural information remains available as stimuli remain on the screen to build up the study

display, and is minimum in Experiment 4 which precludes configural encoding by never presenting all stimuli together. Nevertheless, simultaneous and sequential presentation modes were not directly compared in these experiments, and there was simply no aim or attempt to employ any physiological measure.

In conclusion, in most behavioral experiments, simultaneous presentation is confounded with location information. Studies with fMRI [Coull *et al.*, 2003; Shafritz *et al.*, 2002] also did not consider location as an independent variable to unravel this confound. Considering that there were no studies orthogonally manipulating mode of presentation and locations, the present researcher intended to compare binding under simultaneous and sequential presentation conditions, with the stimuli presented in unchanged and random locations, in behavioral experiments, and with fMRI.

All experiments in this research use color and shape binding to assess visual feature binding with a change detection task. The primary intention is to contrast simultaneous and sequential presentation. Location is manipulated as the second variable with two levels, unchanged and random, from study to test display. Manipulating location as an independent variable orthogonal to mode of presentation, removes the confound with simultaneous presentation, and allows the assessment of the independent and interactive effects of the two variables.

The present researcher intends to assess behavioral as well as brain level response in the fMRI environment. Behavioral results help understand the interaction of location with presentation modes and how performance is changed when these variables are manipulated. The fMRI results focus on the cortical regions commonly activated due to each level of each independent variable. The fMRI results also highlight the interaction of the two independent variables in specific regions of the brain. In sum, they show the difference between presentation modes in the functioning of the brain.

This research will contribute to the theoretical understanding of the binding process. The difference between spatial and temporal distribution of objects will help in understanding how the distribution of visual stimuli over space and time affect binding in human behavior. Importantly, the research will throw some light on the relation of these two modes of presentation with location information, held to be so crucial for binding. Additionally, the research will reveal the extent to which the attentional resources and processes of visual working memory [VWM] are used in binding of stimuli presented simultaneously and sequentially.

These advances in theoretical understanding also have a huge practical importance, as intact feature binding is a dependent measure of the healthy brain. Healthy aging apparently does not lead to binding deficits [Brown and Brockmole, 2010; Parra *et al.*, 2010; but see Peich *et al.*, 2013]. However, brain injuries invariably impair the ability to bind [Friedman-Hill *et al.*, 1995]. Various studies show that binding is disrupted in many neuropsychological disorders such as schizophrenia [Gold *et al.*, 2003], Alzheimer's disease [Parra *et al.*, 2014], Parkinson's disease [Zokaei *et al.*, 2014], and autism [Bowler *et al.*, 2014]. Specifically regarding visual feature binding, Parra *et al.* [2010] found that binding capability differentiated between healthy controls and familial early onset Alzheimer's disease carriers, who were otherwise asymptotic at the time of test. Thus, binding deficits are considered a cognitive marker of Alzheimer's disease [Kozlova *et al.*, 2020]. In contrast to Parra *et al.* [2014] and Kozlova *et al.* [2020] who did not find color shape binding deficits among patients of Parkinson's disease, Zokaei *et al.* [2014] reported significant differences in binding performance between healthy controls and Parkinson's patients, with the performance of Parkinson's patients being lower than the healthy controls. Perhaps, this is because they tested binding of color with orientation for six stimuli presented sequentially. The present research, which focuses on differences due simultaneous and

sequential presentation, in binding tests with and without locations, is also likely to throw light on such conflicting results of vital importance. The growing consensus is that different kinds of bindings, involving distinct features, and requiring different types of attention exist [e.g., Hitch *et al.*, 2020; Jaswal and Logie, 2013]. Thus, differential assessment, diagnosis, and rehabilitation of neuropsychological disorders could benefit with the knowledge generated by studies such as the current work.

The organization of the thesis is as follows. The present chapter contains only a brief introduction. This is followed by Chapter 2, which reviews the literature related to feature binding and elaborates the need for the present research in the light of studies already done in this area. Chapter 3 contains the information about the general method and procedure used to perform the experiments and analyze the results. Chapters 4 and 5 describe the behavioral experiments, give their results, and discuss them. Chapter 6 describes the experiment carried out in the fMRI environment. Chapter 7 is a general discussion of the behavioral as well as imaging data. Chapter 8 recapitulates the research work and major contributions in a summary, and concludes with delineating future possibilities.