

Spatial working memory for clustered and linear configurations of sites in a virtual reality foraging task

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Abstract Two experiments using an immersive virtual reality foraging environment determined the spatial strategies spontaneously deployed by people in a foraging task and the effects on immediate serial recall of trajectories through the foraging space, which could conform or violate specific organisational constraints. People benefitted from the use of organised search patterns when attempting to monitor their travel through either a clustered “patchy” space or a matrix of locations. The results are discussed within a comparative framework.

Keywords Working memory · Spatial strategies · Primates · Virtual reality

Introduction

Working Memory (WM) is related to general mental capacity and higher human cognitive skills (Baddeley 2003; Cowan 2005). Thus, comparative studies of WM have the potential to clarify what could be idiosyncratic of human cognition and provide information about its evolution. Spatial WM enables the temporary retention of locations. The non-verbal nature of the tasks used to measure it makes it suitable for comparative studies. Spatial WM has been assessed in children and animals with foraging-type tasks requiring the exhaustive exploration of a set of baited containers within a foraging space (see De Lillo 2012, for a review; and Cramer and Gallistel 1997, for an example of the related “travelling-salesman” problem). There, in any given trial subjects, need to track the

locations explored to avoid costly errors consisting in re-visiting containers from which the reward has been collected. Importantly, the geometric arrangement of the containers and the order in which they are visited affects search efficiency. This relationship between the spatial configuration of containers, search patterns and efficiency is particularly evident in primates. Monkeys (*Cebus apella*) minimise the number of errors when exploring containers arranged in spatial clusters and their search efficiency is correlated with the use of strategies that involve depleting all containers within a given cluster before moving to another cluster (De Lillo et al. 1997). This ability is not shown by non-primate species studied with similar paradigms (e.g. Valsecchi et al. 2000) and could be related to high level functions that monkeys may share with humans. Unfortunately, assessing this possibility by testing humans with foraging tasks is made impractical by the need to use large-scale unfamiliar environments in conditions affording the control of all the relevant variables. Moreover, although useful to sample search strategies spontaneously deployed by different organisms, foraging tasks only afford correlational investigations of the relationship between spatial strategies and WM performance.

The experimental study of the interplay of the geometric arrangement of spatial items, the patterns used to select them and spatial WM has been carried out using immediate serial spatial recall (ISSR) tasks, such as variations of the Corsi test (1972). In computerised versions of this task, icons in different locations on a touch screen flash in sequence and participants have to touch them in the correct order. Using clustered arrays of locations, it has been possible to show that human ISSR is more accurate for patterns similar to those spontaneously deployed by monkeys in similarly structured foraging environments (De Lillo 2004; De Lillo and Lesk 2010). Humans also benefit

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from spatial structure in ISSR tasks where items are arranged as a square matrix. There, sequences with consecutive items within the same row, column or diagonal are reproduced more accurately than sequences violating this principle (Bor et al. 2003).

Although ISSR and foraging can provide complementary information regarding the relationship between spatial structure, search organisation and memory performance, there are important differences between these tasks. ISSR tasks are implemented in much smaller environments and, crucially, they offer a bird's eye view of the search space not available to subjects walking throughout a foraging environment. When the configuration of items is presented frontally to the subject, the perception of shapes generated by the serial pattern of flashing icons is likely to play a role in their encoding. Indeed, it has been suggested that the benefits of organised ISSR patterns within a matrix of items derives from chunking them into visual *gestalten* (Bor et al. 2003). Thus, it is important to assess effects of structure in foraging tasks where the subject navigates through the environment with limited perceptual access to the structure of the overall foraging space compared to typical ISSR tests.

Experiment 1 used a virtual foraging task to assess organisational principles spontaneously deployed by humans when freely exploring items arranged in clusters or as a square matrix. Experiment 2 used the same large immersive virtual foraging environments to assess ISSR for navigational trajectories, which could conform to or violate specific forms of serial-spatial structure.

Experiment 1

Methods

Eight female and 2 male participants (age 18–36 years) were tested in a Virtual Reality (VR) laboratory. Vizard 3.0 software enabled the presentation of a virtual environment consisting of a set of 9 poles surmounted by a white sphere within a large virtual hall with richly textured surfaces and a variety of landmarks (see Fig. 1) via an NVIS nVisor stereoscopic head mounted display. An Inter-Sense position tracker determined the viewpoint depending on the head and body movement of the participants, who operated a wand to navigate and produce responses.

In each trial, participants were required to select each of the 9 poles in any order. A pole was selected by navigating towards it, placing a hand visible within the virtual display (see Fig. 1) on the sphere surmounting it, and pulling the wand trigger. A brief message confirmed that the location had been “visited” but no cues were left to mark visited locations. Performance was measured as the average number of visit to poles. In any trial, optimal performance

would be evidenced by the use of 9 visits to search the set of poles. Visits in excess of this indicated errors deriving from returning to poles already selected. Depending on the condition, the poles were arranged as a 3×3 square matrix (Fig. 1b) or in clusters (Fig. 1a), with an inter-pole distance within a cluster being half of the minimum distance between clusters. Participants received 6 trials alternating matrix and clusters with the condition of the starting trial counterbalanced. The facing direction at the beginning of each trial was randomised across trials.

Results and discussion

The average number of visits to poles was 9.07 (SD = .20) in the clusters and 9.47 (SD = .99) in the matrix condition. Unsurprisingly, considering the nearly optimal performance in both conditions, the two means were not statistically different.

The trajectories followed in the clustered configuration always featured the exhaustive exploration of a cluster before moving onto the next. On the single occasion where errors occurred, they were due to a second exploration of all the items within a cluster already visited. In all trials except one, when searching the matrix, subjects performed consecutive visits to locations within the same row, column or diagonal, and all poles within a line or column were exhaustively explored before moving to a pole in another line or row. The single trial where this did not happen required 23 pole visits to complete. The results of Experiment 1 are consistent with the notion that organisational constraints spontaneously deployed by people minimise the memory demands of the foraging task but does not warrant the inference of a causal relationship between these factors. Experiment 2 probed the nature of such relationship with an ISSR task implemented in the same virtual foraging environment.

Experiment 2

Methods

Experiment 2 was carried out 1 day after the completion of Experiment 1, using the same apparatus and environments.

Experiment 2, featured a presentation and a recall phase. In the presentation phase, one of the white spheres surmounting the poles turned red until the participant approached and selected it. A second pole would then turn red, and so on, until the 9 poles were selected. The recall phase then began. The starting position was reinstated, and participants had to recall the sequence of the presentation phase by selecting the poles, in the same order. The spheres remained white at all times during this phase.

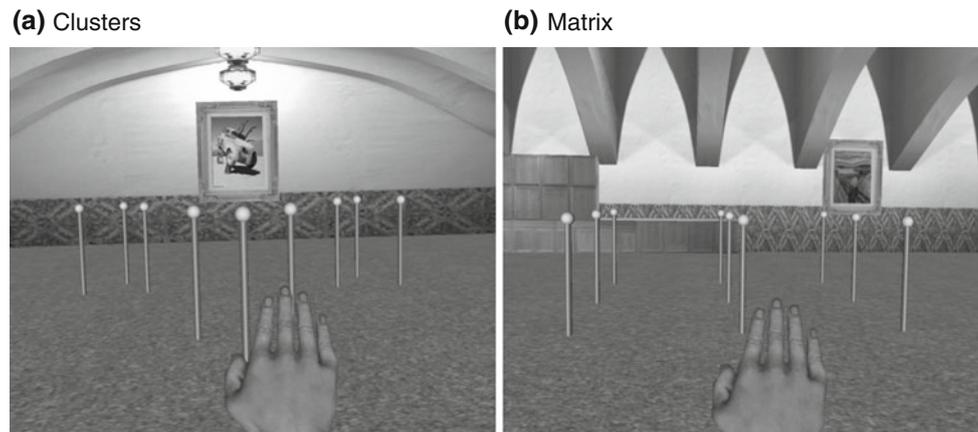


Fig. 1 Examples of views of the VR foraging space: **a** clusters, **b** matrix. Apart from the arrangement of poles, the environment was the same in both conditions

Each trial featured either the clusters or the matrix configuration of poles and the to-be-recalled sequences could be either structured or unstructured. Structured sequences in the clustered condition featured consecutive items within the same cluster until the cluster was exhaustively explored; unstructured sequences always had consecutive items in different clusters. Structured sequences in the matrix condition had consecutive items within the same row, column or diagonal, whereas non-structured sequences always violated this constraint. Participants received, in random order, 6 trials for each condition according to a 2 (configuration: clusters/matrix) \times 2 (structure: structured/unstructured) repeated measure design.

Results and discussion

Figure 2a shows the proportion of poles selected in the correct order in the 4 conditions. A 2 (configuration) \times 2 (structure) ANOVA carried out on these values showed a higher level of recall in structured sequences [$F(1, 9) = 38.88, p < .001, \eta_p^2 = .81$]. Neither the effect of configuration nor the interaction structure by configuration proved significant.

A time analysis provided converging results. The mean RT for correct responses in each condition is presented Fig. 2b. The same ANOVA carried out on these values revealed faster RT for structured sequences [$F(1, 9) = 48.87, p < .001, \eta_p^2 = .85$] but no effects of configuration or interactions.

Experiment 2 clarifies that there is a dependency between organisational principles and spatial WM in humans. Benefits of spatial structure in humans have been observed in ISSR tasks (Bor et al. 2003; De Lillo 2004; De Lillo and Lesk 2010) where the configuration of items is laid out in front of the observer and shown to play an important role in sequence encoding (Avons 2007). The

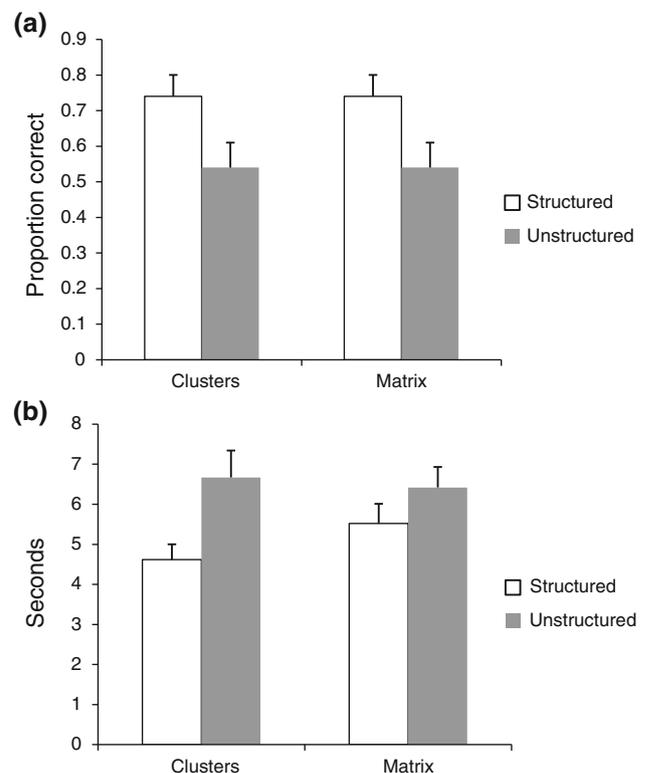


Fig. 2 Proportion of poles selected in the correct order (**a**) and RT (**b**) recorded in each condition of Experiment 2. Error bars 1 SE

results of this experiment indicate that the benefits of organisation are also evident when people navigate through the set of locations in a large virtual foraging environment.

Conclusions

The present study suggests that the use of immersive virtual reality foraging environments can provide information

about human spatial WM that can usefully inform comparative analyses. Experiment 1 suggested that in a clustered foraging space, humans deploy strategies that are not dissimilar to those of other primates (*Cebus apella*) tested in real-life environments (De Lillo et al. 1997). Interestingly, humans were also extremely proficient when searching foraging spaces with locations arranged in a matrix, where other primates forage less efficiently.

A difference between humans and monkeys (*Papio papio*) in the ability to benefit from linear constraints in a matrix arrangement of locations has been observed in ISSR tasks implemented with small arrays such as in variations of the Corsi test (Fagot and De Lillo 2011). Differences between the ability of humans and monkeys to benefit from structure in such tasks may reflect interspecies differences in perceptual grouping and would be consistent with the large body of results on the differences in global/local visual processing and perceptual organisation of monkeys and humans (e.g. Fagot and Deruelle 1997; Spinozzi et al. 2009; De Lillo et al. 2011). However, the present results indicate that humans impose strategies and benefit from spatial structure in a task where the contribution of visual perceptual grouping would be less obvious and a useful bird's eye representation of the configuration of the search space would need to be actively constructed by the subjects on the basis of local viewpoints experienced through navigation. The differences between a real-life foraging spaces used with monkeys and the VR environment used here with people invite caution when comparing data. Nevertheless, in both environments not all target locations could be seen from every viewpoint. Thus, our results make it plausible that the differences in the ability to benefit from linear structures between humans and monkeys may extend beyond visual organisation to the memory coding of spatial information. The characterisation of such differences may determine whether there are unique aspects of human cognition that can be detected with the tasks featured here and which may provide vital information concerning the plausibility of primate models of human memory.

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