1 Introduction

Behavioural, physiological and connectionist models of paired associates learning (PAL) and serial learning (SL) can be classified as those that treat either PAL or SL alone, tacitly assuming distinct underlying cognitive processes [1, 2, 3, 4] and those that, more parsimoniously, treat both types of memory within the same modelling framework [5, 6, 7, 8]. Two major behavioural findings apparently dissociate PAL and SL. First, in SL there is an advantage for cued recall probes in the forward direction over probes in the backward direction [9]; in PAL, symmetry holds [10, 11]. Second, the correlation between accuracy on forward and backward probes of a paired associate is near-perfect [12, 13, 14], but forward and backward probes of a long list of items exhibit a substantially lowered correlation [9]. While this could be used to suggest that PAL and SL are subserved by distinct systems with different dynamics, Caplan [5, 6] showed how one can still treat SL and PAL within a single theoretical framework. In this view, the PAL and SL paradigms represent ends of a continuum spanned by a single parameter controlling the degree to which neighbouring pairs of items are isolated from the rest of the list. Differences in performance between PAL and SL may thus be largely attributed to differential effects of interference from other list items. The Isolation Principle predicted a dissociation in the correlation between probe directions when moving from pairs of items even to the next smallest number of items: three.

We present three types of tests of the notion that PAL and SL may be subserved by identical underlying mechanisms. First, we show behavioural data that confirms some of the predictions of the prior analytical and simulated models. Second, we present new, task-specific simulations showing that models that incorporate the Isolation Principle account for additional properties of the data. Finally, we present analyses of electroencephalographic data that support the notion that many cognitive processes underlying successful study of pairs are identical to those underlying successful study of triples.

2 Methods

2.1 The pair/triple task

Participants first viewed a fixation, followed by a pure list of 9 word pairs or 6 word triples (EEG experiment) or a mixed list containing 2 pairs and 4 triples (behavioural experiment), in a single study trial. Next they performed a short, four-question arithmetic distractor task and finally, they answered either 12 (behaviour) or 6 (EEG) cued recall questions based on the list. Cued recall probes consisted of a single item and a string of question marks, and could be in either the forward or backward direction. Thus, pairs (AB) could be probed with A? or ?B. Triples could be probed either with A? or ?B ("AB-triples") or with B? or ?C ("BC-triples"). We denote the excluded item of the triple (the word that is neither the probe nor the target item; C for AB-triples and A for BC-triples) the "triple-lure" item. A session consisted of 18 (behaviour) or 23 (EEG) such lists.

2.2 The model

The model is a an associative chain, built by adding heteroassociations (outer products) between pairs of item vectors; all nearest-neighbour associations, plus next-to-nearest-neighbour associations were stored. The model operates much like that used in [5], but with additional parameters for list-to-list variability, output encoding and forgetting, as well as a winner-take-all responding rule rather than a probabilistic Luce Choice rule. A single parameter,

S, determines the degree of isolation between pairs/triples and the rest of the list by controlling the ratio of within-pair/triple associative strength to between-pair/triple associative strength. Cued recall operates by multiplying the memory matrix with a probe word vector to attempt to retrieve the correctly associated word vector.

2.3 Electroencephalographic methods

EEG activity was recorded from three participants at a 500 Hz sampling rate, on a 65 channel cap, referenced to Cz. Eye movements were removed using a Principle Component Analysis and the signal was re-referenced to an average reference. Trials with amplitude exceeding 100 μV at any channel were excluded from analysis. The data were analysed using two types of Partial Least Squares (PLS) analysis [15], which involves applying a singular value decomposition to a partial correlation matrix between the task design and activity as a function of EEG channel and time bin (40 ms). First, brain activity during study of each word of the pairs and triples was analysed to uncover latent variables (patterns of brain activity that explain a substantial proportion of covariance across a specific task contrast) related to overall study processes. Second, a behavioural PLS method was applied to this study activity, to reveal patterns of brain activity that correlated with subsequent memory test performance across presentation of different words of pairs and triples. Significance was assessed using bootstraps and permutation tests.

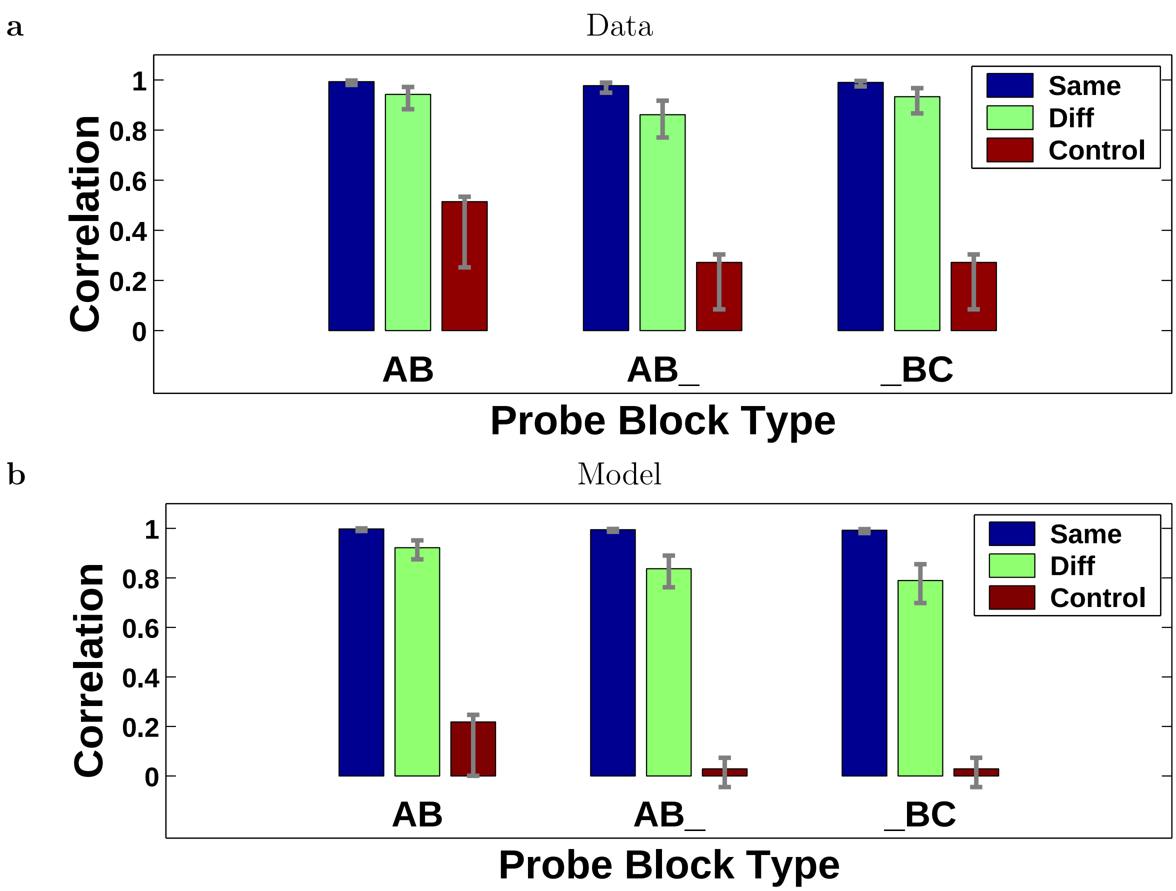

Figure 1: Correlation values from the behavioural data (**a**) and the best-fitting model (**b**). Error bars represent 95% confidence intervals.

3 Results and Discussion

3.1 Behavioural task and simulation

The model was fitted to the accuracy data and control correlation (control for list-to-list variability; see Figure 1) only. The best-fitting model (selected using a genetic algorithm; rmsd=0.020) was then used to produce the remaining correlation values as well as the within-list intrusion patterns and these were compared with the data.

Correlations Figure 1 shows the correlation values for the data (panel a) and the model (panel b), for pairs, AB-triples and BC-triples. The "Same" correlation is a control for the maximum possible correlation; it is the correlation between test 1 and test 2 in the same direction. The "Control" correlation controls for list-to-list variability and represents a lower bound on the possible correlation; it is computed between test 1 and test 2 taken from different pairs or triples from a given list. Finally, the correlation of interest is labelled "Different," and is computed between test 1 and test 2 of a pair or triple when the two tests are in opposite direction. The Different correlation is reduced for triples compared to pairs, as predicted by the Isolation Principle (Figure 1). The magnitude of the effect, however, is much smaller than that found in long serial lists [6]. Nonetheless, without fitting directly to the correlations, the model correctly produces this dissociation.

The model also reproduces another feature of the correlation pattern, namely, that the Control correlation is also reduced for probes of triples as compared to probes of pairs. This can be understood as originating from the same mechanism that caused the Different correlation to be reduced for triples. That is, there is no counterpart of the triple-lure item for pairs. This triple-lure item acts to increase the amount of interference for triples. Because the responding rule is a competitive choice rule, this will tend to counteract any effects of list-to-list variability for triples, but for pairs, there is less interference overall, thus not as much response competition to counteract the list-to-list variability.

Within-list intrusions As predicted by the Isolation Principle, there is a slight adjacency effect (intrusions to a probe tend to come from nearby pairs or triples), but intrusions from the triple-lure item (neither the probe nor the target) dominates by far all other types of intrusions (Figure 2). Without fitting directly to intrusion data, the model captures these qualitative features.

3.2 Electroencephalography: Partial Least Squares analyses

The task PLS analysis produced a single significant latent variable, accounting for 61% of the cross-block covariance. The pattern of activity implicated in this latent variable (not shown) comprised a slow shift, with a positive posterior component and a frontal negative component, beginning at 300–500 ms following word onset. This pattern is high for the late items within pairs and triples but is flipped in polarity for the A items. The "task LV", which shows how the identified pattern of brain activity varies as a function of task conditions, is show in Figure 3; saliences can be interpreted like factor scores in a factor analysis. The task profile differentiated the position of the item within the pair or triple. Furthermore, it resulted in a similar pattern of task saliences for pairs, AB-triples and BC-triples. The similarity of the two types of triples represents an internal replication, but the similarity of the salience pattern between pairs and triples provides direct support for the hypothesis that study of pairs and triples is subserved by the same cognitive processes. This is even more compelling given that participants were informed as to whether they were studying

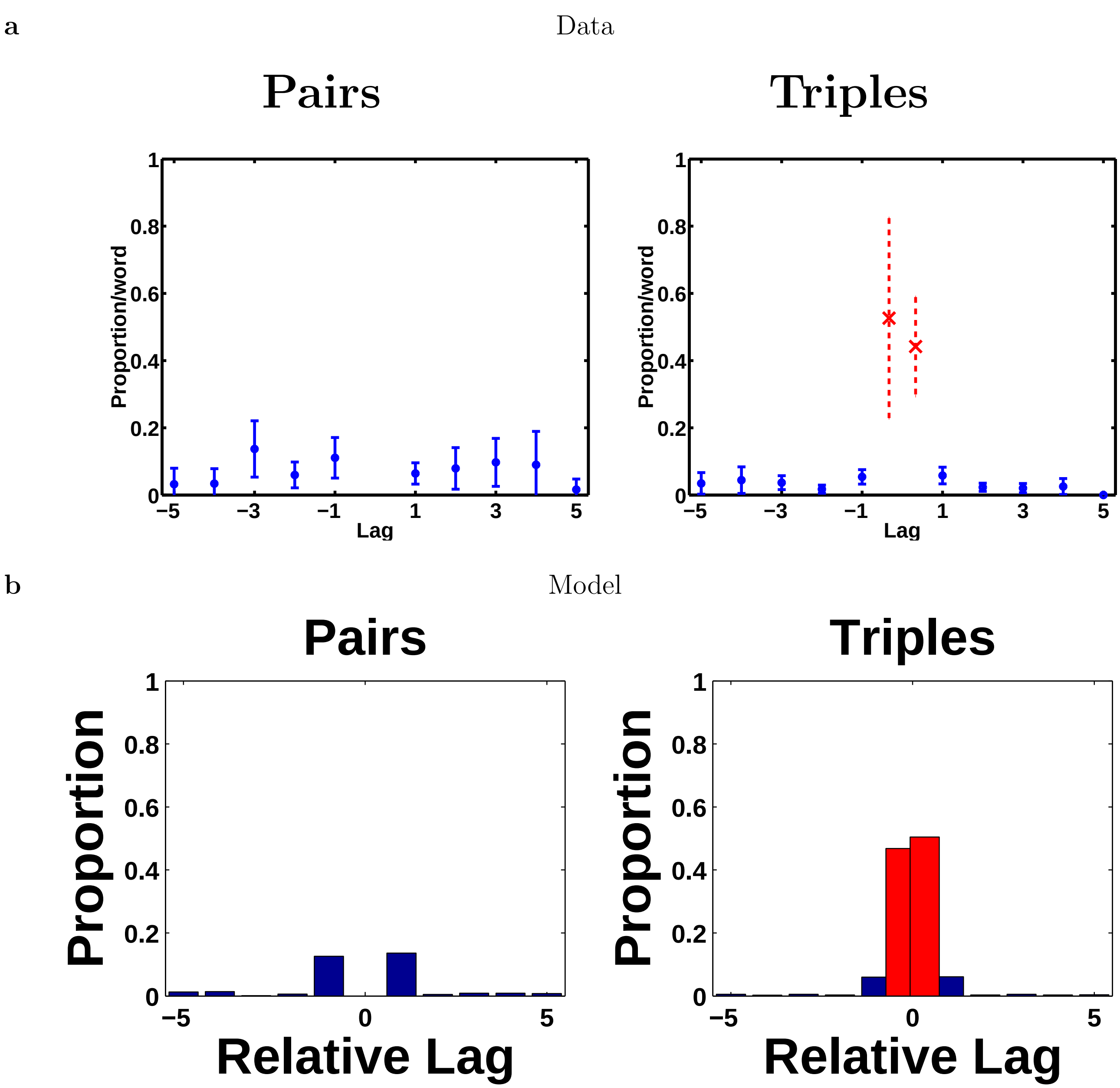

Figure 2: Within-list intrusion rates from the behavioural data (**a**) and the best-fitting model (**b**). The values on the vertical axis reflect rates per item. The horizontal axis denotes relative lag to the pair/triple where the intrusion came from. The red points and bars denote the rates of triple-lure intrusions; there is no counterpart for pairs.

lists of pairs or triples. Thus, this predominant latent variable suggests that the bulk of the brain activity present during study was similar. One consequence of this is that if the set of processes present during study processes are well matched, then we can follow-up and ask what subsets of those study processes predict subsequent cued recall accuracy and response times.

A follow-up behavioural PLS analysis (not shown) related activity at study with subsequent accuracy and response time. This analysis revealed four significant latent variables. One of these again showed a similar pattern of saliences for pairs and both types of triples, identifying common study processes relevant to subsequent test performance. The other three latent variables distinguished pairs from both types of triples, pairs and AB-triples from BC-triples, and all three types of word blocks. These patterns of brain activity may partially reflect differences in active study strategies during presentation of pairs and triples, but also some differences in what studied information is accessed at retrieval. Further analysis is required to determine whether these patterns support or reject a common theoretical framework for memory for associations and lists. Nonetheless, the finding that pairs and triples could only be differentiated by comparing with later test-related behaviour supports the notion that behavioural dissociations between PAL and SL result from processes at test rather than differential processing at study.

4 Conclusion

Cognitive neuroscientists must attempt to link brain activity to behavioural measures and models of cognitive processes, in a rigourous way. We presented the beginning stages of such a research programme. The work was motivated by initial observations from behavioural experiments. This inspired the Isolation Principle in an effort to explain both PAL and SL within a common theoretical framework. The theoretical work then suggested follow-up behavioural and electrophysiological experiments. The resulting behavioural and physiological measures are meaningfully connected to each other, as well as informing and constraining theory. In this way, we hope to generate increasingly specific hypotheses about the meaning of brain activity with respect to models of cognitive processes, enhancing the theoretical significance of both physiological, as well as behavioural experiments.

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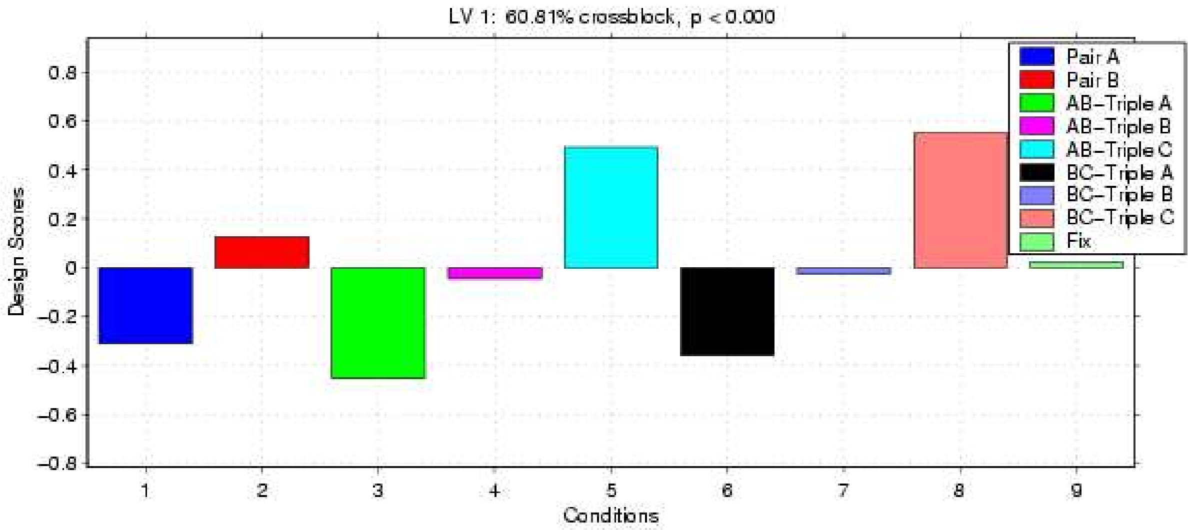

Figure 3: First latent variable from the task PLS analysis. The bar graph plots the relationship of this latent variable to the task (task saliences). "Fix" refers to the Fixation periods. "AB"-triples were subsequently probed with either A? or ?B, whereas "BC"-triples were tested on B? or ?C.

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