

# *The working memory model and the relationship between immediate serial recall and free recall*

Article

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**The Working Memory Model and the relationship between  
immediate serial recall and immediate free recall**

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9 **The Working Memory Model and the relationship between immediate serial recall and**  
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31 **Author note**

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35 Osth and Dennis (2015, JEPLM&C): <https://osf.io/8zycm/>  
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**Abstract**

The effects of speech-based variables on the immediate serial recall (ISR) task constitute fundamental evidence underpinning the concept of the Phonological Loop component of Working Memory. Somewhat surprisingly, the Phonological Loop has yet to be applied to the immediate free recall (IFR) task even though both tasks share similar memoranda and presentation methods. We believe that the separation of theories of ISR and IFR has contributed to the historical divergence between the Working Memory and Episodic Memory literatures. We review more recent evidence showing that the two tasks are approached by participants in similar ways, with similar encoding and rehearsal strategies, and are similarly affected by manipulations of word length, phonological similarity, articulatory suppression/concurrent articulation, and irrelevant speech/sound. We present new analyses showing that the outputs of the two tasks share similar runs of successive items that include the first and last items— which we term start- and end-sequences, respectively – that the remaining residual items exhibit strong recency effects, and that start- and end-sequences impose constraints on output order that help account for error transposition gradients in ISR. Such analyses suggest that similar mechanisms might convey serial order information in the two tasks. We believe that recency effects are often underappreciated in theories of ISR, and IFR mechanisms could generate error transpositions. We hope that our review and new analyses encourage greater theoretical integration between ISR and IFR, and between the Working Memory and Episodic Memory literatures.

**Keywords:** free recall, serial recall, primacy effect, recency effect, working memory, transposition errors

## Introduction

It is difficult to overstate the importance of the *Working Memory Model* (WMM, Baddeley, 1986; Baddeley & Hitch, 1974, 2019) to the examination of immediate memory and its role in higher-order cognitive processes, such as reading, comprehension, reasoning, and learning (for an impressive list of applications, see Baddeley, Hitch, & Allen, 2021). The WMM is highly intuitive and readily understandable, has impressive longevity with relatively infrequent developments (most notably, Baddeley, 1986; 2000), and has served first as a pioneering framework, then a relatively stable leading account, and finally a point of departure for alternative theories (e.g., Andrade, 2001; Conway, Jarrold, Kane, Miyake & Towse, 2008; Gathercole, 1996, 2001; Miyake & Shah, 1999).

This article focuses on the most developed component of the WMM, the Phonological Loop, which embodies the intuitive ideas that we rapidly forget even small amounts of verbal information unless we actively maintain these items through rehearsal. The Phonological Loop was proposed to explain the effects of speech-based variables on the immediate serial recall (ISR) task, and also to help explain the short-term retention of verbal material during higher-order cognitive tasks such as reasoning, comprehension, and learning (Baddeley & Hitch, 1974), chess (Robbins et al., 1996), and task switching (Baddeley, Chincotta, & Adlam, 2001). Over time, a cognitive toolbox has been developed to explore the role of working memory in an impressive range of tasks and participant populations. As well as examining the effects of speech-based variables on the ISR task, this toolbox includes examining the effect of impeding the Phonological Loop by using a concurrent digit load and examining the relative impairments caused by concurrent articulation vs visuo-spatial tapping.

In this article, we address whether the Phonological Loop account of ISR could and / or should be extended to the highly-related immediate free recall (IFR) task (for an earlier consideration of this issue, see Ward, 2001). We review recent evidence that encourages the theoretical integration of the two tasks, and we consider four issues that we believe must be addressed before the Phonological Loop model can be successfully applied to the IFR task including: the role of rehearsal and the effects of speech-based variables in the two tasks, the contribution of episodic (long-term) memory to immediate recall in the two tasks, the importance of modality and recency effects in the two tasks, and the way in which serial position is represented. In our considerations, we argue that the magnitude of recency effects in ISR is often under-appreciated since, owing to earlier omissions in recall, recency items are often output too early to score as correct in conventional serial order

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3 scoring. By contrast, we show that in both tasks, participants often recall sequences of consecutively presented  
4 items that either initiate with the first list item (runs that we term *start-sequences*) and/or that culminate with the  
5 final list item (runs that we term *end-sequences*). We further show that given the known information inherent in  
6 start- and end-sequences, any other recalled item will tend to be positioned at or close to its correct output  
7 position, such that the benchmark locality constraint in ISR (the tendency for incorrectly ordered items to be  
8 recalled in neighbouring output positions) could arise in the absence of any further position information for  
9 these incorrectly ordered items. In this way, we suggest that the serial position effects and output orders in ISR  
10 and IFR may be generated using similar memory mechanisms, that the ISR data need not necessitate positional  
11 coding, and the similarities may encourage further theoretical integration of the two tasks. We argue that a  
12 speech-based verbal rehearsal mechanism, such as the Phonological Loop, could contribute to an integrated  
13 account of ISR and IFR, and argue that this may be so, but only as an auxiliary mechanism supporting  
14 maintenance and retrieval from episodic long-term memory.

### 27 **The historical separation of IFR and ISR**

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29 One might think it surprising that the Phonological Loop has not yet been extended from the ISR task to the IFR  
30 task. Both tasks share highly similar methodologies: in each task, participants are presented with sequences of  
31 (typically verbal) stimuli, one at a time, and at the end of the list, participants must try to recall as many of the  
32 list items as they can in either the same order as they had been presented (ISR) or in any order that they wish  
33 (IFR). Both tasks also share a common theoretical heritage, providing classic empirical evidence that has been  
34 key to the development of the concept of a limited-capacity short-term memory store (STS), namely, the  
35 memory span limitations in ISR and the recency effect in IFR (the recall advantage for the last few list items).  
36 Despite these similarities, the Phonological Loop account of ISR (like many other accounts of short-term or  
37 working memory) has not as yet been applied to the related IFR task, whereas most classic and contemporary  
38 accounts of IFR (like many accounts of episodic memory) have not as yet been applied to the related ISR task.  
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51 As reviewed by Ward, Tan and Grenfell-Essam (2010), there are at least three reasons for the historical  
52 divergence between the ISR (working memory) and the IFR (episodic memory) literatures. First, when  
53 participants are asked to learn a 16-word list for free recall, the magnitude of the recency effect in free recall is  
54 unaffected by the concurrent requirement to maintain a 6-digit sequence for ISR (Baddeley & Hitch, 1974,  
55 1977; Bhatarah, Ward, & Tan, 2006). This finding appears to show that the recency effect in IFR and the  
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3 memory span in ISR cannot both be attributed to the same STS, because one would have expected catastrophic  
4 trade-offs between recency and ISR if the sequences of 6 digits and the last few words were underpinned by the  
5 same limited-capacity store. Thus, “it is suggested that working memory, which in other respects can be  
6 regarded as a modified STS, does not provide the basis for recency” (Baddeley & Hitch, 1974, p. 81) and  
7 “working memory is supposed to have both buffer-storage and control-processing functions, with recency  
8 explained by a separate mechanism” (Baddeley & Hitch, 1974, p. 82).

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16 Second, early reviews suggested that ISR was affected by speech-based variables giving rise to the phonological  
17 similarity effect, the word length effect, the effects of articulatory suppression and unattended or irrelevant  
18 speech<sup>1</sup>, whereas the recency effect in IFR was not particularly sensitive to these variables (e.g., Baddeley,  
19 1976; p. 182). This again suggested that the mechanisms for maintaining and retrieving the items in ISR are  
20 different from those used to output the most recent items in IFR.

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28 Finally, there are clear differences in the shapes of the serial position curves observed in classic ISR and IFR  
29 data sets. The serial position curves in IFR (e.g., Glanzer & Cunitz, 1966; Murdock, 1962; Postman & Phillips,  
30 1965) are characterised by smaller primacy effects (the recall advantage for the items presented at the beginning  
31 of the list) and larger recency effects; whereas the serial position curves in ISR are characterised by larger  
32 primacy effects and reduced recency effects (e.g., Conrad & Hull, 1964; Drewnowski & Murdock, 1980;  
33 Jahnke, 1963). Theories of IFR have tended to focus on the mechanisms underpinning the recency effect (e.g.,  
34 Beaman & Morton, 2000; Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Howard &  
35 Kahana, 2002; Lehman & Malmberg, 2013; Raaijmakers & Shiffrin, 1981; Tan & Ward, 2000), whereas  
36 theories of ISR have tended to focus on the mechanisms underpinning the primacy effect (e.g., Hurlstone, in  
37 press; Lewandowsky & Farrell, 2008; Page & Norris, 1998).

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49 The WMM is far from alone in explaining just one of the two immediate recall tasks. Many classic and  
50 contemporary theories of ISR do not also account for IFR (e.g., Baddeley, 1986, 2000, 2007; 2012; Baddeley &  
51 Hitch, 1974; 2019; Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1992, 1999, 2006; Farrell &  
52 Lewandowsky, 2002, 2008; Henson, 1998; Logan & Cox, 2021; Nairne, 1990; Neath & Nairne, 1995; Oberauer

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<sup>1</sup> In later writings, articulatory suppression and irrelevant or unattended speech effects are often referred to using  
the more theoretically neutral terms “concurrent articulation” and “irrelevant sound” effects (e.g., Beaman &  
Jones, 1997). Here, we deliberately use the original terms to emphasise the assumed links to speech processing.



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3 & Lewandowsky, 2008; Page & Norris, 1998; Saint-Aubin, Yearsley, Poirier, Cyr & Guitard, 2021). Similarly,  
4 many classic and contemporary accounts of IFR do not also account for ISR (e.g., Davelaar et al., 2005; Gillund  
5 & Shiffrin, 1984; Healey & Kahana, 2016; Howard & Kahana, 2002; Laming, 2006, 2008, 2009, 2010; Lehman  
6 & Malmberg, 2013; Lohnas, Polyn, & Kahana, 2015; Polyn, Norman, & Kahana, 2009; Raaijmakers & Shiffrin,  
7 1981; Sederberg, Howard & Kahana, 2008; Tan & Ward, 2000).

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14 However, a growing body of evidence suggests that results obtained from IFR and ISR may converge when the  
15 two tasks are examined using similar methods, list lengths, and scoring systems (Ward, Tan & Grenfell-Essam,  
16 2010). Historically, classic studies of IFR have examined recall of longer lists of 10-40 words and have scored  
17 recalled words as correct irrespective of their order of recall (FR scoring). By contrast, classic studies of ISR  
18 have examined recall using shorter lists of 5-8 words and have scored recalled words as correct only if they are  
19 output in the same serial position as that in which they had been presented (SR scoring). It is possible that  
20 differences previously observed between the two tasks could reflect differences in list length and scoring  
21 systems – decisions taken by the experimenter - rather than a more fundamental difference between the memory  
22 mechanisms used to undertake the tasks by the participant. When the two tasks are examined under more similar  
23 conditions, more recent evidence suggests that there is a need for theoretical integration between the two tasks.  
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### 36 **The case for theoretical integration between ISR and IFR**

37 Four existing lines of evidence support the case for integration. First, the two tasks are encoded and rehearsed in  
38 similar ways (Bhatarah, Ward & Tan, 2008; Bhatarah, Ward, Smith & Hayes, 2009; Grenfell-Essam & Ward,  
39 2012). Bhatarah et al. (2008) presented three groups of participants with lists of 8 words for immediate recall.  
40 One group of participants (pre-cued ISR) were told in advance that they would always be asked to recall the  
41 words in the same order as they had been presented. A second group of participants (pre-cued IFR) were told in  
42 advance that they would always be asked to recall the words in any order that they wished. A final group of  
43 participants were presented with lists of 8 words for immediate recall but were only told after the last list item  
44 had been encoded (but prior to recall) that they would be asked to recall in either the same order (post-cued ISR)  
45 or recall in any order (post-cued IFR). Bhatarah et al. found that the shapes of the serial position curves were  
46 relatively unaffected by knowing the task in advance. Characteristic U-shaped serial position curves were  
47 observed in the two IFR conditions (plotted using FR scoring) that were very similar whether the test was  
48 expected and predictable (pre-cued IFR) or unpredictable (post-cued IFR). Similarly, extended primacy effects  
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3 with little or no recency were observed in the two ISR conditions (using SR scoring) regardless of whether the  
4 task was known in advance (pre-cued ISR) or not (post-cued ISR). These findings were replicated by Bhatarah  
5 et al. (2009) who also showed that the patterns of rehearsals were broadly similar across the four conditions.  
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10 Second, there is growing appreciation that both tasks show a tendency for forward-ordered recall, even though  
11 this is not a formal task requirement in free recall (Bhatarah et al., 2008; Kahana, 1996; Howard & Kahana,  
12 1999; Golomb, Peelle, Addis & Kahana, & Wingfield, 2008; Klein Addis & Kahana, 2005; see also Beaman &  
13 Jones, 1998). Indeed, temporal contiguity occurs across a wide range of tasks, stimuli, and timescales in  
14 episodic memory (Healey, Long & Kahana, 2019).  
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22 Third, there are similarities in the effects of a range of different variables on IFR and ISR, including  
23 presentation rate (Bhatarah et al., 2009), presentation modality (Grenfell-Essam, Ward & Tan, 2017), temporal  
24 isolation (Grenfell-Essam, Ward, & Cortis Mack, 2019), and temporal grouping (Spurgeon, Ward, Matthews, &  
25 Farrell, 2015). Figure 1 shows the effects on ISR and IFR of three of the four effects that are most commonly  
26 associated with the Phonological Loop: phonological similarity (Spurgeon, Ward, & Matthews, 2014), word  
27 length (Bhatarah, Ward, Smith & Hayes, 2009), and articulatory suppression (Spurgeon et al., 2014). In all  
28 cases, speech-based effects that are assumed to be the signatures of the Phonological loop in ISR are also  
29 observed in IFR. To this could be added the effects of irrelevant speech which has been shown to similarly  
30 affect IFR and ISR (see Beaman & Jones, 1998, Figure 1). In both tasks, speech-based variables thought to  
31 affect the ability to rehearse (namely, articulatory suppression and word length) appear to have the greatest  
32 effect on the early serial positions.  
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52 Finally, these similarities increase when using the same list lengths and scoring systems. With short lists,  
53 participants tend to initiate recall with the first list item in both tasks and when they do, recall tends to proceed  
54 in forward order, resulting in elevated recall of early list items and reduced recency effects. For example, when  
55 presented with a short list of random words for IFR, such as “cat, house, fog, stairs” there is a strong tendency  
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3 for participants to recall the list in exactly the same order as presented, i.e., recall “cat, house, fog, stairs” even  
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5 though forward-ordered recall is not a task requirement in IFR (Corballis, 1967; Neath & Crowder, 1996;  
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7 Grenfell-Essam & Ward, 2012; Ward, Tan & Grenfell-Essam, 2010). With far longer lists, participants in both  
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9 tasks find it hard to initiate recall with the first list item and instead initiate recall with one of the last four  
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11 words, recall then tends to continue in forward order, resulting in extended recency effects and reduced primacy  
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13 effects (Grenfell-Essam & Ward, 2012; Ward et al., 2010).  
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### 16 **Issues when applying the Phonological Loop account of ISR to IFR**

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18 If one accepts that IFR and ISR may be more similar than was once assumed, then how can theoretical  
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20 integration be accomplished? Only a few theorists have tried to model both IFR and ISR within the same  
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22 framework (Anderson, Bothell, Lebiere & Matessa, 1998; Brown, Neath & Chater, 2007; Farrell, 2012;  
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24 Grossberg & Pearson, 2008). None of these computational models are attempts to implement the Phonological  
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26 Loop construct and, of these, the model by Anderson et al. (1998) relies upon different processes (involving  
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28 different parameters and different parameter values) for recalling items in IFR and ISR, and both the model by  
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30 Anderson et al. (1998) and that of Grossberg and Pearson (2008) assume very different rehearsal patterns in the  
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32 two tasks, an assumption that seem at odds with the data by Bhatarah et al. (2008, 2009) and Grenfell-Essam  
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34 and Ward (2012), both of which suggest that the two tasks are encoded and rehearsed in similar ways. The  
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36 models of Brown et al. (2007) and Farrell (2012) are more promising, in that they specifically attempt to unify  
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38 short-term and episodic memory, although the former says little about output orders in recall, and neither  
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40 account include mechanisms for rehearsal, a mechanism central to the WMM. We will return to a more  
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42 extended discussion of the Farrell (2012) model in a later section.  
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46 If we put aside integrative models from outside the broader working memory framework, and take instead the  
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48 Phonological Loop account of ISR as our starting point, then what issues must be addressed before it can  
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50 contribute to an integrated account of ISR and IFR? In what follows we consider, in turn, the following four  
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52 issues:

- 53 (1) What is the nature of rehearsal and speech-based variables in immediate recall tasks?
  - 54 (2) What is the contribution of episodic (long-term) memory in these immediate recall tasks?
  - 55 (3) What is the nature of modality effects and recency effects in immediate recall?
  - 56 (4) How is serial order represented in the two tasks?
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5 *What is the nature of rehearsal and speech-based variables in the recall in the two tasks?*

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7 Our first issue concerns the putative role of verbal rehearsal and the effects of speech-based variables on ISR  
8 and IFR (but for contrasting reviews on the causal role of rehearsal on immediate recall, see Lewandowsky &  
9 Oberauer, 2015; Oberauer, 2019; Ward, in press). Phonological Loop theorists have championed the importance  
10 of speech-based variables in determining the memory span and accuracy in ISR. To many, it is highly intuitive  
11 that ISR should be linked with covert speech and verbal rehearsal and so be affected by factors such as  
12 phonological similarity, word length, irrelevant speech, and articulatory suppression. It is arguably one of the  
13 more impressive and coherent aspects of the WMM that it explains the interactions between the modality of  
14 presentation, articulatory suppression, and the phonological similarity and word length effects in ISR (Baddeley,  
15 1986; Baddeley, Lewis, & Vallar, 1984; although see also Hughes, submitted; Jones, Macken & Nicholls,  
16 2004). The importance of speech-based variables in determining accuracy in IFR as well as ISR (see Figure 1)  
17 suggests a common theoretical interpretation: to the extent that the Phonological Loop can account for the ISR  
18 data, it seems reasonable that it should also be applied to the IFR data. Despite this, no theory of IFR has to our  
19 knowledge tried to model the effects of these speech-based variables, even though the effects of phonological  
20 similarity (Spurgeon, Ward & Matthews, 2014), irrelevant speech (Beaman & Jones, 1998), word length  
21 (Bhatarah et al., 2009) and articulatory suppression (Bhatarah et al., 2009; Spurgeon, Ward & Matthews, 2014)  
22 are all found in both tasks, and similar rehearsal patterns are seen in IFR and ISR (Bhatarah et al., 2009).

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24 Numerous studies have also shown that differences in memory spans between individuals and between different  
25 types of stimuli reflect differences in rehearsal rates between participants (e.g., Hulme et al., 1984; Naveh-  
26 Benjamin & Ayres, 1986) and between the speech rates of the stimuli (e.g., Baddeley, Thomson & Buchanan,  
27 1975; Ellis & Hennesly, 1980; Murray & Jones, 2002; Schweikert & Boruff, 1986; Standing et al., 1980),  
28 respectively. In IFR, there is considerable evidence that the probability of recall is also a positive function of the  
29 number of rehearsals (Rundus, 1971), the recency of the rehearsals (Brodie & Murdock, 1977), and the  
30 distribution of the rehearsals (Modigliani & Hedges, 1987), with all three variables most likely to be important  
31 (see Tan & Ward, 2000; Ward & Tan, 2023). Rehearsal can also reorder the presented stimuli in IFR as  
32 rehearsal and reminding leading to subjective re-organisation (Ward & Tan, 2023). Verbal or articulatory  
33 rehearsal therefore likely represents a common element in the two tasks.

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3 Although performance in IFR and ISR tends to benefit from greater opportunities to rehearse, it is important not  
4 to overstate the role of rehearsal in these tasks. It is well-established that not all differences in memory span  
5 between different stimulus materials can be attributed to differences in rehearsal rates, but rather spans are  
6 additionally affected by long-term lexical knowledge concerning words (e.g., Hulme, Brown & Maughan, 1991)  
7 and the co-occurrence of words (G. Jones & Macken, 2018), including such things as word frequency effects  
8 (e.g., Hulme et al., 1997), concreteness effects (Walker & Hulme, 1999), orthographic and phonological  
9 neighbourhood effects (Roodenrys et al., 2002), and semantic factors (e.g., Poirier & Saint-Aubin, 1995; Saint-  
10 Aubin & Poirier, 1999). In addition, recent evidence suggests that the retention of order in ISR through  
11 rehearsal is most effective if rehearsal is limited to subspan sequences of stimuli (Barrioulet, Gorin & Camos,  
12 2021; Jarrold, 2017). If one encourages and instructs participants to rehearse greater sequence lengths than  
13 would have been spontaneously generated then ISR accuracy does not improve (Souza & Oberauer, 2018,  
14 2020). Critically, both ISR and IFR can be performed in situations where verbal rehearsal is less likely (albeit  
15 performance is sometimes reduced), such as with faster presentation rates (e.g., Oberauer, 2022; Tan & Ward,  
16 2008), with articulatory suppression (e.g., Grenfell-Essam, Ward, & Tan, 2013; Oberauer, 2022; Spurgeon et al.,  
17 2014), or with non-verbal stimuli (Cortis, Dent, Kennett & Ward, 2015; Jones, Farrand, Stuart & Morris, 1995;  
18 Ward, Avons, & Mason, 2005).

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36 Moreover, it is important to note that rehearsal is often assumed to serve a different function in ISR and IFR. In  
37 the WMM, a primary function of rehearsal is to refresh the activation of phonological codes of the presented  
38 items in the Phonological Store that would otherwise suffer trace decay if left unrehearsed. That is, the function  
39 of rehearsal is to offset a negative effect associated with time (trace decay). In contrast, theories of IFR assume a  
40 more positive function for rehearsal. Yes, theories of IFR may assume that an unrehearsed item may become  
41 less accessible following a delay (due to changes in temporal distinctiveness or context discrimination, or  
42 increased competitiveness of other list items), but rehearsing an item in theories of IFR is generally thought to  
43 strengthen the associations between itself and the current list in LTM (Raaijmakers & Shiffrin, 1981), the  
44 associations between itself and other co-rehearsed items (Raaijmakers & Shiffrin, 1981), or to increase its later  
45 accessibility from episodic memory by providing multiple different retrieval routes and multiple different  
46 contexts (including more recent contexts) in which it was encoded (Tan & Ward, 2000). Arguably, rehearsal  
47 must do more than simply maintain the original level of activation. Increased rehearsals and repetitions of  
48 stimuli increase the probability of recall of those stimuli in both tasks as evidenced by higher accuracies with  
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3 slower presentation rates in IFR (Glanzer & Cunitz, 1966; Murdock, 1962; Roberts, 1972; Tan & Ward, 2000)  
4 and in ISR (Oberauer, 2022; Tan & Ward, 2008).  
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9 *What is the contribution of episodic (long-term) memory in these immediate recall tasks?*

10 In a revision of the WMM, Baddeley (2000) proposed the need to incorporate an Episodic Buffer. The Episodic  
11 Buffer was envisaged as a limited-capacity temporary storage system that holds episodes of integrated  
12 information across space and potentially over time from a variety of sources and codes. The revision was  
13 proposed following discussion of many of the limitations of rehearsal also raised by us in the preceding  
14 paragraphs, and importantly, to confront the need to relate WM with LTM. In the revision, the contributions of  
15 the episodic buffer and episodic long-term memory to ISR were not specified, other than to suggest it acted as a  
16 “back-up store” in those situations (e.g., conditions with visual presentation and articulatory suppression) where  
17 the operation of the Phonological Loop was unlikely. Phenomena such as the Hebb repetition effect (Hebb,  
18 1961), the superior recall of sequences of items that have previously been presented as part of a to-be-recalled  
19 list, and the effects of long-term (e.g., lexical) knowledge provide evidence for one kind of contribution of long-  
20 term memory to ISR but these are generally considered as reflecting the build-up of knowledge over time rather  
21 than a direct episodic recollection (Baddeley, Gathercole & Papagno, 1998). However, we believe that some  
22 contribution of episodic memory must surely also be expected in ISR beyond this, given that participants can  
23 readily recall list items from prior lists in a delayed free recall test (e.g., Loaiza & McCabe, 2012; McCabe,  
24 2008) and participants benefit from their repetition in spin lists (e.g., Kahana, Mollison, & Addis, 2010; Solway,  
25 Murdock, & Kahana, 2012) and serial learning and multi-trial free recall learning tasks (e.g., Klein, Addis &  
26 Kahana, 2005; Waugh, 1961).  
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45 By contrast, all theories of IFR specify the contribution of episodic long-term memory during encoding and  
46 retrieval (Brown, Neath & Chater, 2007; Crowder, 1993; Greene, 1992; Howard & Kahana, 2002; Lohnas et al.,  
47 2015; Polyn et al., 2009). Indeed, many theories of IFR assume that *all* encoding and retrieval is from episodic  
48 memory, but many additionally propose the need for recall from a STS (e.g., Atkinson & Shiffrin, 1971;  
49 Davelaar et al., 2005; Lehman & Malmberg, 2013; Raaijmakers & Shiffrin, 1981; Unsworth & Engle, 2007).  
50 For those who assume that IFR is a two-component task (see e.g., Baddeley, 1986; Glanzer, 1972): the recall of  
51 words presented at early and middle serial positions are assumed to be retrieved from long-term episodic  
52 memory (and so are selectively affected by variables such as presentation rate, word frequency, and list length),  
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3 whereas the most recent items are assumed to be directly retrieved from a separate STS (and so are selectively  
4 affected by variables such as the modality of presentation and the presence of a filled delay). What is lacking  
5 therefore is a more-specified account of what, if any, role is played by the Episodic Buffer and episodic LTM in  
6 WMM accounts of ISR (and IFR).  
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12 *What is the nature of modality and recency effects in immediate recall?*

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14 The Phonological Loop is predominantly a theory of rehearsal and forward-ordered recall and as such it does  
15 not readily account for the modality effect in ISR, nor recency effects, more generally. The modality effect  
16 refers to the enhanced recall of items presented auditorily rather than visually within the recency portion of the  
17 serial position curve (e.g., Beaman, 2002; Beaman & Morton, 2000; Conrad & Hull, 1968; Crowder & Morton,  
18 1969; Grenfell-Essam, Ward & Tan, 2017). Although one would think that an explanation of the modality effect  
19 should be explicable within the WMM framework, Baddeley, (1986, p.87) stated that “while a complete model  
20 of the working memory system would most certainly incorporate this interesting and productive area of  
21 research, the model has at present little to say on these phenomena.” To our minds, some of the intuitive appeal  
22 of the WMM is lost by its inability to capture the recall advantage of the last few items presented. Modality  
23 effects occur with both serial and free recall, although the magnitude of the auditory advantage is typically  
24 observed to be greater in serial recall (near perfect recall for the final item) but a smaller auditory advantage  
25 tends to be extended across far more serial positions in free recall. These apparent discrepancies can be  
26 explained by the difference in list lengths that are typically used. As shown by Grenfell-Essam, Ward and Tan  
27 (2017), the magnitudes and the extents of the modality effects in the two tasks tend to converge when the list  
28 lengths are equated, and an “inverted modality effect”, the superior performance for visual presentation at  
29 earlier points in the list (Beaman, 2002), is also observed in both tasks (Grenfell-Essam et al., 2017). Thus,  
30 while a complete explanation of the modality effect must encompass a variety of data not included here (for  
31 example, the effects of a post-stimulus suffix and the nature of lip-read and non-verbal recency; Campbell &  
32 Dodd, 1980; Greene & Samuel, 1986) there is no *a priori* reason to dismiss a common account covering both  
33 serial and free recall.  
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54 An explanation of the recency effect is also critical for any extension of the WMM to IFR. We have already  
55 mentioned prior research that showed that the magnitude of the recency effect was relatively unaffected by a  
56 concurrent digit span task (Baddeley & Hitch, 1974, 1977), studies that had suggested that recency lies outside  
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3 the WMM. Subsequent studies further suggested that recency effects occur across a wide range of timescales  
4 (Baddeley, 1986, chapter 7; Baddeley, 2007, chapter 6; da Costa Pinto & Baddeley, 1991; Hitch & Ferguson,  
5 1991), consistent with the ratio rule of Glenberg and Swanson (1986). As we will see, the ideas of long-term  
6 recency through temporal distinctiveness (Glenberg & Swanson, 1986) and discrimination of fluctuating  
7 temporal context (Estes, 1955; Mensink & Raaijmakers, 1989) have been highly influential in contemporary  
8 accounts of IFR (Brown et al., 2007; Howard & Kahana, 2002). Although Baddeley and Hitch (1993) later  
9 suggested an implicit priming interpretation of these effects, the idea that recency is delivered by an explicit  
10 retrieval strategy operating on presented stimuli provides a promising starting point for the extension of the  
11 WMM to IFR. Once a list of words had been presented, participants could flexibly elect to use either of two  
12 separate retrieval cues: an explicit retrieval cue that would generate recency from episodic long-term memory or  
13 a separate cue to initiate forward-ordered recall from the start of the list using the Phonological Loop. If this  
14 were the case, then one might consider why participants would not also use the recency-based cue to assist in  
15 ISR? As we will see, the magnitude of the recency effect is underappreciated in most theories and data sets  
16 concerning ISR.  
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### 32 *How is serial order represented in the two tasks?*

33 Finally, perhaps the biggest challenge for extending the Phonological Loop to IFR arises when one considers  
34 how serial position information is represented across the two tasks. The WMM (Baddeley, 1986; Baddeley &  
35 Hitch, 1974) provided qualitative accounts of working memory phenomena without specifying the mechanisms  
36 for retaining serial order information. Subsequent computational models of ISR have been developed to model  
37 these working memory phenomena, with many directly inspired by the Phonological Loop. Henson (1998,  
38 2001) proposed three categories of proposed serial order mechanisms: ordinal theories, positional theories, and  
39 associative chaining theories. Many theories of ISR incorporate multiple mechanisms to deliver all the working  
40 memory phenomena (for more detailed review of theories of ISR, see Lewandowsky & Farrell, 2008; Hurlstone,  
41 in press; Hurlstone, Hitch & Baddeley, 2014; Osth & Hurlstone, 2023) but these serial order mechanisms are  
42 primarily proposed to produce forward-ordered primacy effects. However, we would like to argue that an  
43 integrated account of ISR and IFR must be capable of generating both primacy and recency effects, and there  
44 must be scope, even with ISR, to allow participants to demonstrate their undoubted cognitive flexibility and  
45 output in different orders using task-appropriate retrieval strategies. For example, the bulk of the data on ISR  
46 has been obtained by asking participants to recall a list in the order in which it was presented, starting with the  
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3 first item. However, studies have also looked at backward serial recall using an ISR paradigm (e.g., Li &  
4 Lewandowsky, 1995) and it is straightforward to show that participants are capable of initiating ordered recall  
5 (and, presumably, rehearsal) from an arbitrary given point if required to do so (Beaman, 2002).  
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10 Computational models of the Phonological Loop have tended to use ordinal and/ or positional mechanisms for  
11 serial order. Ordinal theories of serial recall assume that earlier list items are encoded more strongly than later  
12 list items (Farrell & Lewandowsky, 2002; Grossberg & Pearson, 2008; Page & Norris, 1998) resulting in a  
13 primacy gradient extending across the early serial positions. At each point in serial recall, the most activated  
14 item is selected, output, and then that response is suppressed, before the next most activated item is selected, and  
15 so on. This process gives rise to extended primacy effects and one item recency (due to the edge effect). Noise is  
16 added at response selection, and the resulting errors are most typically transpositions where a later stimulus item  
17 becomes more highly activated than its immediately preceding list item, and so is output too soon, followed by  
18 *fill in*, the recall of the next highly activated item which tends to be its transposed partner. Errors tend to be  
19 transpositions between near-neighbouring list items (the locality constraint), but omissions and item errors are  
20 also observed, their frequencies increase across output positions (due to decay or interference).  
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34 Positional theories assume that each stimulus item is associated with an abstract representation of its list  
35 position or temporal context. At test, it is assumed that participants can retrieve the positional marker or reset  
36 the temporal context to that associated with the first list item and the positional marker is assumed to evolve  
37 during test, iteratively cueing successive list positions. In some models, the context evolves with new events  
38 (Burgess & Hitch, 1992; Farrell, 2006; Lewandowsky & Farrell, 2008) whereas in others, the context is more  
39 closely associated with time (Brown et al., 2000; Brown, Neath & Chater, 2007; Burgess & Hitch, 1999, 2006;  
40 Hartley et al., 2016). The list position is normally referenced by its distance from the start of the list, but it can  
41 also be referenced by its distance from the end of the list (Henson, 1998) - which must be an unrealistic  
42 assumption if the list length varies markedly and unpredictably across successive lists (see Grenfell-Essam &  
43 Ward, 2012; below). Many positional theories also assume primacy gradients (Brown et al., 2000; Burgess &  
44 Hitch, 1999, Henson, 1999, Lewandowsky & Farrell, 2008).  
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57 Computational models of the Phonological Loop have tended to reject associative chaining models of serial  
58 order. Simple associative chaining models (e.g., Lewandowsky & Murdock, 1989) assume that each presented  
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3 item is associated with its predecessor. Compound chaining models (Murdock, 1993, 1995; Solway et al., 2012)  
4 assume forward and backward associations between both adjacent and non-adjacent items; the strengths of the  
5 associations decrease across different positions. At test, some additional mechanism is required to access the  
6 first list item such as a start of list cue (Lewandowsky & Murdock, 1989), but the representation of the list could  
7 be encoded across all items (Logan, 2021; Logan & Cox, 2021, 2023) and used at test. There are perceived  
8 difficulties in how simple associative chaining models can generate the locality constraint, how they deal with  
9 lists containing repeated stimuli, and how they can model participants' ability to recover from error. Moreover,  
10 it is often assumed that associative chaining models should have particular difficulty in recalling lists that  
11 alternate between phonological similar and dissimilar list items (Baddeley, 1968; Henson et al., 1996), but these  
12 difficulties can be overcome if (like many other accounts of ISR) one assumes separate layers dealing with order  
13 and items (see Osth & Hurlstone, 2023).

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26 By contrast, while all theories of IFR explain the bowed serial position curves, not all theories of IFR  
27 satisfactorily explain output order. In dual-store theories of free recall, it is assumed that participants output first  
28 the contents of STS (the order in which the items are output is rarely stated) before long-term memory is  
29 searched using the list context as a cue, after which additional retrieved items can also be used as cues. Words  
30 that are rehearsed during study will increase their associative strength with the list context, and co-rehearsed  
31 items will increase their inter-item associative strength. Primacy effects in dual-store accounts of IFR are  
32 typically explained by increased rehearsal of the early list items (Raaijmakers & Shiffrin, 1981; Rundus, 1971).  
33 However, recall is probabilistic and there is no guarantee that the recency items or the primacy items will be  
34 recalled from STS or LTS in forward serial order. Other accounts predict primacy effects and recency effects  
35 based on the increased temporal distinctiveness of the first and particularly the last items (Brown, Neath &  
36 Chater, 2007), but there is again no clear mechanism proposed to order output in IFR, and a positional code is  
37 necessary to additionally account for ISR. Finally, some accounts of IFR assume that the start of list context  
38 (Davelaar et al., 2005; Metcalfe & Murdock, 1981) or "Get Ready" warning signal (Laming, 1999, 2010) are  
39 encoded and retrieved at test to give access to the start of the list. Latency data show that initiating recall with  
40 the first list item is far slower than initiating recall with one of the more recent list items (Laming, 1999; Osth &  
41 Farrell, 2019; Osth, Reed, & Farrell, 2021), which can be taken as evidence that initiating recall with the first  
42 item or later items involve different retrieval decisions. Thus, with the exception of the position coding of  
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perhaps the first list item, many of these theories of IFR have not used ordinal or positional coding to code serial position.

The accounts of IFR that provide the most detailed accounts of output orders are the Context Maintenance and Retrieval (CMR) theories (e.g., Healey & Kahana, 2016; Kahana, 2020; Lohnas et al., 2015; Polyn et al., 2009) derived from the Temporal Context Model (TCM, Howard & Kahana, 2002). In these models, successive stimuli are associated with a temporal context that evolves throughout the presentation of the list. Unlike earlier models that had assumed that temporal context randomly drifts with time (e.g., Estes, 1955; Glenberg & Swanson, 1986; Mensink & Raaijmakers, 1988), in TCM and its CMR variants, it is the pre-experimental associations to presented stimuli that are retrieved and used to drive the changes in the temporal context. In this way, later stimulus items are encoded with temporal contexts that accommodate a recency-weighted function of recently experienced list items.

These models readily explain recency effects in IFR: the end of the list context is used to cue recall and owing to its greater overlap with the contexts associated with more recent items, the end of list context is most likely to cue one of the most recent list items. These models also assume temporal regularities in the output order: it is assumed that the retrieved context of a recalled item is used as a cue and so neighbouring items are most likely recalled, with heightened tendency to recall the next list item (asymmetric temporal contiguity effect). Some primacy can be incorporated by assuming that the early list items are more strongly attended to and/or are more strongly encoded. However, most experimental data sets modelled by TCM and its variants are of relatively long lists during which participants must perform an orienting task, such that the primacy effect is markedly reduced relative to the recency effect. Some CMR-inspired models have allowed for additional context representation to also code the encoding task (Polyn et al., 2009), the start of the list (Kragel et al, 2015 Morton & Polyn, 2016) or the list context (Healey & Wahlheim, 2024). Interestingly, a list context is also used in recent CMR-inspired models of serial recall (Logan, 2021; Logan & Cox, 2021, 2023), and these CMR-inspired models offer an alternative starting point for theoretical integration of the two tasks. We shall return to these alternative accounts in a section toward the end of the article.

We have already reviewed prior work suggesting that words are rehearsed and encoded in similar ways in IFR and ISR, such that the different serial position curves typical of the two tasks must largely reflect differences in

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3 retrieval strategies, output interference, and scoring systems. In particular, we wish to argue that participants  
4 must have far greater accessibility to the most recent list items in ISR immediately at test, notwithstanding that  
5 strong and extended recency effects are not always observed in ISR serial position curves. We argue that  
6 recency effects are greatly reduced following the output interference of earlier items (Beaman, 2002; Bhatarah  
7 et al., 2008, 2009; Cowan, Saults, Elliot, & Moreno, 2002; Grenfell-Essam & Ward, 2012; Lewandowsky,  
8 Brown & Thomas, 2009; Oberauer, 2003; Tan & Ward, 2007; Ward & Tan, 2019) and that recency effects are  
9 reduced using SR scoring, because SR scoring systems penalise as incorrect the recall of terminal runs of  
10 recency items in recall sequences containing one or more omissions. Thus, we wish to argue that whatever serial  
11 order mechanism(s) are proposed for IFR and ISR, they must be capable of generating both primacy and  
12 recency effects and it should be possible for participants to output in different orders using task-appropriate  
13 retrieval strategies.

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26 To illustrate these points, consider the ISR and IFR data of Grenfell-Essam and Ward (2012, Experiment 3)  
27 presented in Figure 2 in which three groups of participants were presented with lists of between 2 and 15 words  
28 for immediate recall. The words were presented individually on a computer screen at a rate of 1 word per second  
29 and were read aloud by the participants. One group (pre-cued ISR) always knew that they would be required to  
30 perform ISR, and their lists were always prefixed and suffixed with the cue “same”. A second group (pre-cued  
31 IFR) always knew that they would be required to perform IFR, and their lists were always prefixed and suffixed  
32 with the cue “any”. A third group encoded the list items without knowing the required test. Their lists were  
33 always prefixed by the uninformative cue “?????” and the task requirements on that trial were revealed  
34 immediately prior to recall by the suffix cue “same” indicating to recall in the same order (post-cued ISR) or by  
35 the suffix cue “any” indicating to recall in any order (post-cued IFR). After the post-cue, the screen changed to  
36 reveal a grid containing the same number of numbered rows as there were words on the current trial and helped  
37 inform participants of the list length of that trial. Participants always wrote their recalls in response sheets which  
38 contained numbered grids of 15 lines. With ISR instructions, participants could only recall in forwards order,  
39 and participants in all conditions vocalised their written responses as they recalled. A word was scored as  
40 correct if it was output at any grid position in IFR (FR scoring) and was scored as correct only if it was output in  
41 the same grid position as its serial position in ISR (SR scoring).

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--Figure 2 about here--

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The left-hand panels of Figure 2 show the serial position curves of the pre-cued ISR condition (using SR scoring, Figure 2A) and pre-cued IFR conditions (using FR scoring, Figure 2C). It is immediately apparent that accuracy in both tasks reduces with longer lists, and that with task-specific scoring, there is more extended primacy with ISR and more extended recency with IFR. In part, the reduced recency in ISR relative to IFR reflects output interference: in ISR these terminal items can only be recalled after the recall of any earlier list items, whereas in IFR they can be output first. However, when one looks at the panels showing the serial position curves of a pre-cued ISR task, one might also be struck by the finding that as list length increases the recency effects in ISR become more extended than are typically observed using conventional SR scoring. Thus, given the opportunity then it is possible to show recency extending over several serial positions even with ISR. Conversely, the serial position curves of an IFR task show more evidence of primacy at shorter list lengths in terms of a more obvious uplift for the first 1-2 items than is typically seen in free recall using longer lists.

The right-hand panels of Figure 2 show the serial position curves for the post-cued ISR (using SR scoring, Figure 2B) and post-cued IFR conditions (using FR scoring, Figure 2D). The words in these two post-cued conditions must have been encoded in the same way because participants could not reliably anticipate the instructed task prior to recall. Critically, those differences between the ISR and IFR tasks observable in the pre-cued tasks remain in the post-cued conditions when scored in the traditional way. Thus, the serial position curves of the post-cued ISR condition resembled those from the corresponding pre-cued ISR condition (using SR scoring), and the serial position curves of the post-cued IFR condition resemble those from the corresponding pre-cued IFR condition (using FR scoring).

Participants' prior knowledge of the output requirements – which might prompt different encoding and maintenance strategies - cannot therefore be the important factor in creating the differences between IFR and ISR; rather these differences must reflect the action of the experimenter in instructing different recall orders and applying different scoring criteria. This replicates and extends earlier data by Dalezman (1976) showing that post-list instructions on the order in which to prioritise the recall items in an otherwise “free” recall task changes the shape of the serial position curve, primarily by boosting primacy and reducing recency when subjects were

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3 asked to recall the beginning of the list first. Similarly, the recall of earlier recalled items tends to be enhanced  
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5 in versions of ISR, in which participants are instructed to initiate recall at particular points of the list (e.g.,  
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7 Beaman, 2002; Cowan, Saults, Elliott & Moreno, 2002).  
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### 10 **Start- and End-sequences in IFR and ISR**

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12 Until this point, this article has largely reviewed prior existing work that encourages the theoretical integration  
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14 of IFR and ISR. We have argued that to the extent that the Phonological Loop model provides an adequate  
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16 account of ISR, it should also be able to be applied to IFR data. One might reasonably ask how extending the  
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18 model from ISR to IFR might inform what types of serial order information are strictly necessary to account for  
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20 the primacy and recency effects that are observed in Figure 2.  
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24 In this section, we present new analyses re-examining the serial order information contained within the Grenfell-  
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26 Essam and Ward (2012) data. Our starting point is that the WMM and many theories of ISR are not well-placed  
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28 to generate the large and extended recency effects observed in our ISR (and IFR) data, whilst theories of IFR are  
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30 not obviously well placed to output sequences of 5-7 items in correct serial order. How do participants  
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32 performing ISR know that the 14<sup>th</sup> presented item in a 15-item list should be positioned in grid position 14?  
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36 One integrated solution to generate recency effects in ISR (as well as IFR) would be to assume that each  
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38 presented stimulus item is associated with a continuously-evolving temporal context (e.g., Davelaar et al., 2005;  
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40 Glenberg, 1984, 1987; Glenberg & Swanson, 1986; Mensink & Raaijmakers, 1988, 1989; Tan & Ward, 2000);  
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42 and assume further that the retrieved pre-experimental associations of that item help drive the evolution of the  
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44 temporal context (Healey & Kahana, 2016; Howard & Kahana, 2002; Kahana, 2020; Lohnas et al., 2015; Polyn  
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46 et al., 2009). An evolving temporal context encoded at learning, retrieved at recall, and used to cue item  
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48 representations is common to many models of both serial and free recall but in serial recall it is constrained so  
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50 that it reinstates the start of the list context at retrieval. If the end-of-list context is used as a retrieval cue,  
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52 then it is most likely to cue a recent item (e.g.,  $n-2$ ,  $n-1$ , or  $n$ ), which if retrieved, could itself be used to cue  
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54 successive list items. Through the principles of first recency and then temporal contiguity, participants could  
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56 find that they have retrieved one, two, or three consecutively-presented end-of-list items terminating with the  
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58 last list item, i.e., an **end-sequence**, which they could then allocate to the last one, two, or three list positions,  
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60 respectively.

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5 An integrated solution for generating primacy effects in IFR (as well as ISR) would be to assume that  
6 participants at test are able to cue the start of the list (cf. Brown et al., 2000; Burgess & Hitch, 1999; Farrell,  
7 2012; Logan, 2021; Logan & Cox, 2021, 2023). If so, then the retrieved context could be used to retrieve  
8 successive items, creating a run of one, two, three or more consecutively-presented stimulus items starting with  
9 the first list item, i.e., a **start-sequence**. A focus on start- and end-sequences is consistent with early conclusions  
10 from recall studies that stronger or unique retrieval cues are associated with the beginning and ends of lists  
11 (Dalezman, 1976; Tulving, 1968). At slower rates, forward-ordered recall might be augmented further by the  
12 active maintenance of cumulative forward-ordered rehearsal in the Phonological Loop.  
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22 To clarify our novel start- and end-sequence scoring procedure, let us represent an 8-item list of presented words  
23 with the 8 letters, ABCDEFGH. Suppose that in a test of IFR, participants recalled the following four sequences  
24 of recalls: FGHCABG, HGABCE, ABCEGH, GFAC. One way to measure the serial order information present  
25 at recall is to score these recalled sequences in terms of what we call start-sequences and end-sequences. In our  
26 new analyses, a start-sequence is defined as a run of recalls from consecutive serial positions in the original list,  
27 initiating with the first presented word, A. Similarly, an end-sequence is defined as a run of recalls of words  
28 from consecutive serial positions in the original list, terminating with the last presented word, H. If one scores  
29 start-sequences in **bold** and end-sequences in *italics*, then the first sequence of recalls could be expressed as:  
30 *FGHC***ABG** (an end-sequence of three, and a start-sequence of two), with the remaining three sequences of  
31 recall attempts rendered as *HG***ABCE**, **ABC*FEGH*, GFAC. Figure 3 applies the scoring of start- and end-  
32 sequences to the Grenfell-Essam and Ward (2012) data. To be clear, in our new reanalyses, the recalled  
33 sequences refer to the temporally ordered sequence of vocalised words rather than the assigned grid positions at  
34 which the recalled words were written.  
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--Figure 3 about here--  
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57 As Figure 3 shows, there are even more striking similarities between the four serial position curves when the  
58 new start- and end-sequence scoring system is applied to both tasks. Importantly, the forward serial order  
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3 information (start-sequences) that one might assume would be conveyed by the Phonological Loop in the ISR  
4 data appears to be similarly present in the IFR data. In addition, there is considerable recency present in both  
5 tasks as evidenced by the similar end-sequences in both IFR and ISR.  
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10 The start- and end- sequence analyses performed upon the Grenfell-Essam and Ward (2012) data suggest that  
11 theories of IFR and ISR need to be able to generate such start- and end-sequences as recall-entities in their own  
12 right, albeit ones of varying size and scope. One might then reasonably ask, what are the characteristics of the  
13 “Other” items (those recalled items not output in start- or end-sequences), and how might they be recalled?  
14 Figure 4 shows the residual serial position curves which plot the proportion of words recalled as “Other” items  
15 in the four conditions. Unlike most serial position curves which are primacy-justified, plotting serial position 1  
16 on the far left-hand side of the serial position curve, the serial position curves in Figure 4 have been recency-  
17 justified, such that the last list item in each list length are presented on the right-hand side of each panel. The  
18 figure show that for both IFR and ISR there is little residual primacy and considerable residual recency. That is,  
19 the primacy effect observed in Figure 2 appears to come almost entirely from the start-sequences; when these  
20 are removed from the serial position curves as in Figure 4, the “Other” items show little recall advantage for  
21 items near the beginning of the list. By contrast, Figure 4 shows that the recency effect arises not only from the  
22 end-sequences but when the end-sequences are removed, there remains a more general recall advantage for  
23 items less distant from the end of the list, a finding more consistent with recency-based accounts of IFR and  
24 episodic (long-term) memory. This finding could, however, potentially be explained if final list items are not  
25 only more accessible than middle items but have less positional certainty than the primacy items (cf. Henson,  
26 1998).  
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--Figure 4 about here--  
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### 53 **Using start- and end-sequences with more standard ISR data sets**

54 At this point, one might wonder whether our findings are limited to the Grenfell-Essam and Ward (2012) data  
55 set which could be considered somewhat unusual in varying the list length and recalling written serial recall in  
56 lined grids. In this section, we re-examine more standard ISR data from the impressively large data set from  
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Osth and Dennis (2015) who presented four groups of almost 100 participants with 62 experimental trials consisting of lists of 6 words presented at a rate 1.25s per word. A series of three question marks (???) acted as a recall cue for participants to recall the list items in forward serial order by typing in each word followed by the enter key which cleared each response. Participants typed “done” to conclude their recall. The four between-subjects conditions of Osth and Dennis (2015) were the Open condition (6128 trials) in which the stimuli were sampled from an open set (the six words were always different on each trial), the Blanks condition (6186 trials), which also used an open set of stimuli but the participants were encouraged to type “blank” to signal an omission, the Closed condition (6198 trials) in which the stimuli were sampled from a closed set (the same six words were always presented in different random orders on each trial; the set of six words were randomly sampled for each participant from the Open set stimulus pool), and the Reconstruction condition (5797 trials), in which an open set of stimuli and a reconstruction of order test were used (at test, the six list items were re-presented in a new random order and remained in view whilst participants performed recall).

In our second reanalyses, we re-analyse data from these more standard ISR methodologies to examine the extent to which the serial position curves are also determined by the start- and end-sequences. We are interested in the length of the start-sequences and the length of the end- sequences. How much recency is apparent in these more standard ISR data sets and why is there so little recency in the standard serial position curves with ISR scoring? Specifically, we reanalysed the recall sequences on each trial of each participant for the four conditions of Osth and Dennis (2015) and in each recalled sequence, we categorised the recalls as being part of a start-sequence, as being part of an end-sequence, or not in either type of sequence which we categorize as “other”. Table 1 shows the different combinations of start- and end-sequences in the data in the four conditions. First, there were different proportions of trials in which the recalled sequences were completely correct, “123456”, the proportions increasing with the ease of recalling the items. Thus, in the Reconstruction of Order and Closed conditions, where the list items are known at test or were constant from trial to trial, these proportions of completely correct sequences were 0.472 and 0.383, respectively; whereas when the items were unknown and varied from trial to trial, these proportions of completely correct sequences were 0.209 and 0.152, respectively.

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--Table 1 about here--

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3 Table 1 also shows that a good proportion of trials in each group contained different combination of incomplete  
4 “start-” and “end-sequences”. Figures 5A and 5B shows the proportion of words recalled as part of start-  
5 sequences and end-sequences, respectively, when the proportions include the trials in which the recalled  
6 sequences were completely correct; Figures 5C and 5D shows the proportion of words recalled as part of start-  
7 sequences and end-sequences, respectively, when the proportions do not include the trials in which the recalled  
8 sequences were completely correct. As can be seen, there is considerable primacy and recency in these ISR data,  
9 with the primacy effect from the start-sequences being more sensitive to the level of support for the recall of the  
10 items across the four groups (Figure 5C) than the recency in the end-sequences (Figure 5D).

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22 --Figure 5 about here--  
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28 Given the ISR instructions, we assumed that participants would first output the start-sequence, then recall the  
29 “Other” items in a random order, before ending their recall with the end-sequence. Of interest was the patterns  
30 of order errors that were generated using this procedure. In studies of ISR, it is typical to plot error transposition  
31 gradients that show the probability of recalling, in each of the different possible output positions, a word that  
32 had been presented in a given input serial position. Figure 6 shows the error transposition gradients for the four  
33 conditions of Osth and Dennis (2015). Each panel shows the proportion of recalled items as a function of their  
34 input serial position (different coloured lines) across the different output positions (x-axes). The peaks in these  
35 distributions show that the presented words were most often correctly recalled in their correct output position:  
36 e.g., the third presented item was most often recalled third, the fourth presented item was most often recalled  
37 fourth, and so on. Were one to join up the peaks of these distributions, then this provides the serial position  
38 curves. Whilst there is clear evidence of extended primacy effects, there is little or no evidence of recency in  
39 ISR using correct in-position scoring (i.e., little or no recall advantage of outputting the sixth item in the sixth  
40 output position compared with outputting the fifth item in the fifth output position), despite the evidence for  
41 end-sequences in these data (Figure 5, Table 1).

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7 As is typical, words that were recalled in incorrect output positions were typically recalled at near-neighbouring  
8 locations (the locality constraint), a finding that has been argued to support ordinal or positional models. For  
9 example, Henson, Norris, Page & Baddeley (1996) concluded “The present study has shown how detailed  
10 analysis of patterns of errors can shed considerable light on the nature of the mechanisms required in a  
11 successful model of immediate serial recall. *The locality constraint* [the preponderance of errors which are  
12 transpositions of nearby items] *shows that errors arise through mechanisms beyond random guessing.*” (Henson  
13 et al, p.110, italic emphasis added). The patterns of incorrectly ordered recalls are difficult to examine in the  
14 panels of Figure 6 because the proportions of the incorrect responses are small relative to the proportions of the  
15 correct responses. These distributions of incorrectly ordered responses are more easily observed in the left-hand  
16 panels of Figure 7, which do not show the correct recalls, but plot the distributions of incorrectly ordered recalls  
17 as proportions of the total numbers of order errors in that condition. As shown in the left-hand panels of Figure  
18 7, for each presented input serial position, the proportion of incorrectly ordered recalls are greatest at the nearest  
19 neighbouring output positions, clearly illustrating the locality constraint.  
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--Figure 7 about here--  
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Of interest is the representation of serial order that is necessary to generate these error gradients. Why is the word presented in the fourth serial position more often recalled in output positions 3 or 5, rather than at more distant output positions, 2 or 6? Does this suggest that ordinal or positional coding of all items is necessary in ISR data? If so, this might present a barrier to the theoretical integration of ISR and IFR because ordinal or positional coding is rarely assumed in theories of IFR.

As an expository device, we consider an extreme alternative possibility, that participants know *nothing* about the serial position of items that are not recalled as part of a start- or end- sequence. Our analyses will therefore show how much order information is strictly necessary in the recall of 6-item lists for serial recall and so which types of theories of ISR and IFR could potentially explain these data.

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3 For each recalled sequence in the Osth and Dennis (2015) data, we categorized the recalled words as (i) being  
4 part of a start-sequence, (ii) being part of an end-sequence, or (iii) being an “Other” item. Note that “Other”  
5 items therefore include any recalled word that was not part of a start- or end-sequence that was recalled in the  
6 correct or incorrect output position, any list items that were repeated at output (repetitions), and any non-list  
7 items that had been presented on previous trials (prior-list intrusions) or had not been presented on any previous  
8 trial (extra-list intrusions). We assumed that any start-sequence items would be output first, any end-sequence  
9 items would be output last, and any “Other” list items would be randomly allocated to intervening output  
10 positions. The right-hand panels of Figure 7 show the proportion of output errors generated by our  
11 “start+guess+end” estimates. Perhaps surprisingly, our estimated distributions resemble quite closely the  
12 patterns of observed errors in the ISR data, even though we assumed that there was no additional serial position  
13 information contained within the output sequences beyond that contained in the start- and end-sequences.  
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25 There are two main reasons why our estimated distributions of errors closely resemble the observed error  
26 distributions. First, participants often outputted fewer responses than there were words, and in such cases any  
27 end-sequences which were recalled would necessarily be output prematurely in earlier output positions. Second,  
28 although the “Other” items were assumed not to possess any inherent serial position information, their output  
29 positions were nevertheless constrained to lie *between* start- and end-sequences. If one accepts the argument that  
30 start-sequences and end-sequences constrain recall for the mid-list items in a similar way, then something very  
31 like the random guessing that was dismissed by Henson et al. (1996) *a priori* becomes worthy of more serious  
32 consideration<sup>2</sup>.  
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45 <sup>2</sup> It is worth noting some models already implement the benefit of a known end-sequence in serial recall to a  
46 limited extent. For example, the Primacy Model of Page and Norris (1998) simulates the modality effect within  
47 serial recall by assuming Precategorical Acoustic Storage (PAS; Crowder & Morton, 1969) of the final item.  
48 This guarantees near-perfect recall of that item and a “trickle-back” effect across the penultimate and  
49 antepenultimate items as, because the final item is known, it is no longer competing for recall at these positions.  
50 This exclusion of the final item for consideration prior to the end of the list results in superior recall  
51 performance not only for that item itself, but also across the final 2-3 serial positions for auditory lists (see also  
52 Beaman & Morton, 2000).  
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3 The importance of this demonstration is that we have shown that reasonably plausible error transposition  
4 gradients can be generated in ISR even in the absence of positional information associated with these order  
5 errors, just so long as the output order of recalled “other” items is constrained by known start-sequences and  
6 end-sequences. As mentioned earlier, very few theories of free recall assume that items are associated with  
7 detailed serial position information, and so the removal of this constraint widens the range of possible theories  
8 of serial order that could explain serial position phenomena in ISR and IFR. Most primacy effects in IFR arise  
9 through start-sequences, if one removes the start- and end-sequences from IFR data, then the resultant serial  
10 position curves show extended recency, but little residual primacy (e.g., Figure 4). A model of IFR that  
11 generates start- and end-sequences might not only correctly generate the serial position curve in IFR, but make  
12 considerable progress in generating the serial position curves and error transpositions in ISR.  
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23 Before continuing, it is important to acknowledge a number of nuances and limitations that arise from our  
24 analyses. First, we acknowledge that the observed start- and end-sequences that are present in participants’  
25 recall data are unlikely to exactly reflect the start- and end-sequences known by the participant at the time of  
26 test. Indeed, if our hypotheses are correct, then we must assume that the observed start- and end-sequences  
27 which we are starting from are most likely inflated, since they are likely to include the lucky positioning of  
28 “Other” items that through guessing were correctly assigned to extend start- or end-sequences. It is also possible  
29 that through some other cause of failure (e.g., typing error of B to B’) that an item in a known sequence, ABCD,  
30 may be mistyped, AB’CD, such that the observed start sequence appears truncated, deflating the estimated  
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43 It is worth noting some models already implement the benefit of a known end-sequence in serial recall to a  
44 limited extent. For example, the Primacy Model of Page and Norris (1998) simulates the modality effect within  
45 serial recall by assuming Precategorical Acoustic Storage (PAS; Crowder & Morton, 1969) of the final item.  
46 This guarantees near-perfect recall of that item and a “trickle-back” effect across the penultimate and  
47 antepenultimate items as, because the final item is known, it is no longer competing for recall at these positions.  
48 This exclusion of the final item for consideration prior to the end of the list results in superior recall  
49 performance not only for that item itself, but also across the final 2-3 serial positions for auditory lists (see also  
50 Beaman & Morton, 2000).  
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3 sequence length. We further acknowledge that a generative model would help clarify the sufficiency of this  
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5 approach.  
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8 Second, although our analyses could be taken as an important counterpoint to ordinal and positional accounts of  
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10 the locality constraint, we do not rule out the possibility that some or all of the start- and end-sequences and  
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12 transpositions gradients were generated by ordinal or positional codes, nor that some of the start- and end-  
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14 sequences and transpositions gradients arise through guessing. Indeed, assuming that either (i) all transposition  
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16 errors are caused by a confusion of positional cues, or that (ii) no transposition errors are caused by a confusion  
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18 of positional cues could be considered extreme views. Nonetheless, the former is implicitly endorsed by any  
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20 model of serial recall which does not include a (possibly metacognitive) guessing component, which is the  
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22 majority of connectionist models, and our analyses provides an existence-proof that transpositions gradients  
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24 could arise even in the absence of (more or less precise) positional information, given the constraints of start-  
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26 and end-sequences.  
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### 30 **What are the benefits of separate start- and end-sequences?**

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32 The use of different retrieval cues to try to initiate recall of separate start- and end-sequences is consistent with  
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34 the finding that participants tend to initiate IFR with either the first list item or one of the last four list items  
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36 (Ward et al., 2010). Implementing these two cues in different orders would allow participants the flexibility to  
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38 perform IFR (typically end-cue then start-cue) or ISR (necessarily start-cue then end-cue) when instructions are  
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40 post-cued, immediately prior to test (Bhatarah et al., 2008, 2009; Grenfell-Essam & Ward, 2012; Ward & Tan,  
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42 2019). Separate retrieval cues are also consistent with the latency data (Osth & Farrell, 2019; Osth, Reed &  
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44 Farrell, 2021) which show that serial position 1 would be very unlikely to be ever output first based on any  
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46 competitive race between items but must instead be chosen via a separate decision process.  
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50 Separate cues generating start- and end-sequences may help explain why the start and end of a list serve as  
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52 anchors in serial learning and multi-trial free recall learning studies. The use of separate start of list and end of  
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54 list retrieval cues offers a possible way to output some items when one cue fails entirely (such as when a start of  
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56 list cue fails to access any items at increasing list lengths) or when the end of list cue fails (such as when a filled  
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58 retention interval is inserted after the last list item). Since the end-of-list sequence is only generated at retrieval,  
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60 there is no concern about how one encodes an end-of-list marker with widely varying and unpredictable list

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3 lengths (cf. Henson, 1998), and the generated end-sequences are relative to the end of the list and not based on  
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5 input serial position from the start of the list (Henson, 1999).  
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8 A further benefit is that our analyses show that the Error Transposition gradients arise as an emergent property  
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10 of the separate start- and end-sequences and need not be generated by an additional mechanism. Again, the  
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12 suggestion that there are no other mechanisms for coding order is an extreme position, but one which might  
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14 prove fruitful if appraised in conjunction with other considerations. For example, the original version of the  
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16 feature model (Nairne, 1990) was successful in showing phonological confusion errors when list items shared  
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18 (phonologically) similar features, but did not show the correct pattern of errors without the addition of a stage in  
19  
20 which order information was explicitly considered, and perturbation of such order cues was allowed, with cues  
21  
22 more likely to drift or “perturb” to a nearby serial position (Neath, 1999). The reason why error patterns in  
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24 Nairne’s (1990) original feature model were not correct was because each item was recalled independently of all  
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26 the others, with the only constraint on recall being an increasing reluctance to recall any individual item more  
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28 than once, so, in fact, error patterns within the original model were not random, they were systematically  
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30 incorrect. However, if recall is constrained by knowledge of what has already been output, or by consideration  
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32 of what is about to be output, then our analyses show that the choice between the remaining possibilities  
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34 becomes more limited.  
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### 36 **Start- and end-sequences and the WMM**

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38 This article considers whether the Phonological Loop could and / or should be extended from the ISR to the IFR  
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40 task. Our review and new analyses suggest that there are far more similarities than differences between ISR and  
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42 IFR, and we argue that the Phonological Loop should be extended to account for both ISR and IFR data. We  
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44 have shown that speech-based variables, that are traditionally considered to be evidence for the involvement of  
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46 the Phonological Loop in ISR show similar affects also in IFR. We have shown that in both tasks there are start-  
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48 sequences and end-sequences, we suggest that there may be separate retrieval strategies to cue the start and the  
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50 end of the list, and we have provided existence-proof that any non-sequenced “other” words that are recalled can  
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52 be recalled at output positions that are close to the correct position (the locality constraint) even when no  
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54 additional position information is assumed.  
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57 In terms of the WMM, we suggest that a verbal rehearsal mechanism may augment start-sequences.

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59 Supplementary Material A1 confirms that the mean lengths of start-sequences are affected by many variables  
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3 thought to affect rehearsal in the Phonological Loop. The mean length of a start-sequence decreases with  
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5 articulatory suppression (Spurgeon et al., 2014), and decreases with word length (Bhatarah et al., 2009), and  
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7 access to the start of the list decreases with increasing list length (see also Ward et al., 2010). However, it is  
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9 critical to point out that if the Phonological Loop is considered to be involved in the generation and maintenance  
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11 of start-sequences, it should be posited to also generate start-sequences in IFR.  
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15 By contrast, Supplementary Material A2 shows the mean length of end-sequences is far less affected by these  
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17 variables, again, in both IFR and ISR. This suggests that the Phonological Loop concept may be less well-suited  
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19 to explaining participants' ability to cue the end of the list, and the generation of end-sequences. The end-  
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21 sequences and extended recency effects are relatively unaffected by rehearsal, may be used more often with  
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23 longer lists, and they occur even when the list length varies widely and unpredictably from list to list, ruling out  
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25 end list position markers that are encoded with the stimuli (Henson, 1998). By acknowledging the roles of  
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27 recency and episodic long-term memory more generally in ISR, it is potentially possible to preserve the  
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29 importance of phonological loop variables on primacy effects and start-sequences whilst extending the WMM to  
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31 IFR.  
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### 34 **Interpreting start- and end-sequences**

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36 The Phonological Loop and the WMM have until recently been largely agnostic with respect to the mechanism  
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38 used to model serial position information and there are a wide range of possible approaches one could look to  
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40 when exploring the mechanisms for serial order that could generate the start-sequences and end-sequences  
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42 necessary for an integrated account of ISR and IFR.  
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46 One approach would be to start with existing theories of ISR. These include ordinal and positional accounts  
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48 favoured by existing formal models inspired by the Phonological Loop model of serial recall (e.g., Burgess &  
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50 Hitch, 1992, 1999, 2006; Henson et al., 1996; Henson, 1988; Page & Norris, 1998). These mechanisms could  
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52 readily generate Error Transposition gradients by assuming that each item is associated with position or order  
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54 information and that a common type of confusion that can arise at retrieval is in the incorrect positioning of  
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56 items in neighbouring output positions. Although valid, ordinal and positional theories of serial order tend to  
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58 give rise to primacy effects, but our reanalyses of ISR and IFR data suggest that there also exist end-sequences  
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60 and extended recency effects. Recency and end-sequences could be generated by associating stimuli with start-



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3 and end-position markers at encoding (Henson, 1998, 1999), but this only seems plausible with known list  
4 lengths.  
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9 A second approach would be to start with existing theories of IFR. Our novel reanalyses reconceptualise what  
10 serial order information is strictly necessary to generate IFR and ISR patterns of data. Rather than assume that  
11 all list items are encoded with respect to more or less precise position coding, our reanalyses suggests that many  
12 of the serial recall phenomena could be captured by IFR mechanisms, if only they could generate start-  
13 sequences. The leading, most established accounts of IFR are derived from retrieved context theories of episodic  
14 memory (Healey & Kahana, 2016; Howard & Kahana, 2002; Kahana, 2020; Lohnas et al, 2015; Polyn et al.,  
15 2009) that embody the principles of recency and temporal contiguity (Kahana, Diamond, & Aka, in press).  
16 These models assume that items are associated with gradually evolving temporal context; the temporal context  
17 is assumed to evolve in part through the retrieval of pre-experimental semantic associations of the study items,  
18 such that the temporal contexts associated with later items contains a recency-weighted function of the contexts  
19 of earlier-presented items. Most simulations of these theories result in extended recency effects and strong  
20 temporal contiguity effects, but relatively weak primacy effects, and so it has been unclear, until recently,  
21 whether these types of model could generate sufficient primacy or generate the apparently intricate pattern of  
22 error transpositions observed in ISR. However, in the last five years, there has been growing interest and  
23 progress in using TCM-inspired models to model ISR (e.g., CRU, Logan, 2021; Logan & Cox, 2021, 2023). In  
24 the CRU model, the list context is represented within the temporal context that is associated with each item  
25 (enabling it to be used as a start cue) and the temporal context evolves over time, such that the end of list  
26 context has the potential to be used as an end-of list context. Unfortunately, CRU has yet to be applied to IFR.  
27 An alternative possibility is to incorporate a start of list context cue into the evolving temporal context allowing  
28 a CMR-variant (cf. PEPPR, Healey & Wahlheim, 2024; sCMR, Lohnas, 2023) to strategically cue the start or  
29 the end of the list with different retrieval cues. As yet, PEPPR has not been applied to ISR, but sCMR is a  
30 nascent attempt to integrate IFR and ISR. It should also be noted that no variant of TCM or CMR has as yet  
31 incorporated rehearsal mechanisms, and so it is difficult to see how these accounts would deal with the effects  
32 of rehearsal and the phonological loop variables on ISR and IFR.  
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57 A third approach is to start with accounts that already integrate ISR and IFR. Of these, the account by Farrell  
58 (2012) offers the most detailed account of the changes in output orders that are observed in IFR and ISR of lists  
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3 of different lengths. The Farrell (2012) model shows how a serially-ordered short-term or working memory  
4 mechanism – albeit not a deliberate attempt to implement the Phonological Loop construct – might account not  
5 only for serial recall but also for free recall data. Farrell (2012) assumes that a continuously presented list of  
6 items is spontaneously parsed by participants into one or more temporal groups. Individual items are associated  
7 to temporal context using Hebbian association, but unlike many other formal models of ISR and IFR, it assumes  
8 that the temporal context is hierarchically organised, with contexts organised into lists, lists organised into  
9 groups, and within-groups organised by within-group positions. The Farrell model combines many of the core  
10 mechanisms commonly found in formal models of serial recall with concepts from the free recall literature, such  
11 as output interference (Dalezman, 1976) and a stopping criterion at retrieval (Dougherty, Harbison & Davelaar,  
12 2014) to successfully model first ISR and then IFR data. In order to recall an item, participants must first  
13 explicitly retrieve that item's group. Accessing the current group is straightforward, but accessing earlier groups  
14 is far more difficult and may lead to retrieval failure. Once a group has been successfully accessed, recall  
15 proceeds in a forward direction, commencing with the first item in the currently accessed group. Farrell (2012,  
16 pp. 241-242) shows that a model which includes a specific ordering element implemented via the context  
17 vectors not only reproduces patterns of order recall in serial recall, as expected, but simulates memory for items  
18 in free recall uncorrelated with measures of retained order information (Input-Output correspondence or I-O  
19 scores). Critically, the Farrell model offers the flexibility to generate a forward-ordered start-sequences, by  
20 cueing for the first group context, which if successful will tend to generate a primacy-initial run of items, and  
21 offers the flexibility to generate an end-sequences, by cueing with the current context, to generate a terminal run  
22 of list items commencing with the first item in the current group. The Farrell (2012) model is currently the best  
23 published integrated account of IFR and ISR, but it contains multiple mechanisms for generating serial position  
24 information. Our work questions whether all these mechanisms are strictly necessary.

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47 Yet another starting point would have been to focus on the feature characteristics of our stimuli in an attempt to  
48 explain the modality effect. The integrated account that we have sketched out currently says little or nothing  
49 about how a modality effect arises because there is nothing intrinsic to end-sequences *per se* to necessitate such  
50 a thing, albeit that a TCM-inspired account of the modality effect has recently been proposed (Pazdera &  
51 Kahana, 2023). One candidate starting point is the feature model (Nairne, 1988, 1990, 2002; Neath, 2000; Neath  
52 & Nairne, 1995), which assumes that stimuli are represented by a vectors of feature values. Auditory stimuli are  
53 assumed to be more richly encoded than silently-read visual stimuli and so are encoded with a greater number of  
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3 features. The modality effect emerges because successive list items are assumed to overwrite the features of  
4 those immediately preceding them. Since the last list item benefits from not being overwritten, there is a one-  
5 item recency effect, which is greater in auditory lists. In fact, as suggested earlier, the magnitude and the extent  
6 of the modality effect varies with the list length and is present in both ISR (e.g., Conrad & Hull, 1964) and IFR  
7 (e.g., Murdock & Walker, 1969). In both tasks, the size of the recall advantage is smaller but spread over many  
8 terminal serial positions with longer lists and is larger but limited to just a single list item with shorter lists  
9 (Grenfell-Essam, Ward & Tan, 2017). The Grenfell-Essam et al. data show that the magnitude of the modality  
10 effect is far greater when participants initiate their recall from the start of the list and reduced when recall  
11 initiates with the end of the list, suggesting that the modality effect may arise because the recency items are far  
12 more resistant to output interference when they were read aloud or spoken to participants. These data are  
13 consistent with an earlier report by Beaman and Morton (2000) examining free recall only. In Beaman and  
14 Morton's (2000) data, with the exception of auditory recency for the very final item, recency was largely  
15 dependent upon the appearance of end-sequences within the free recall protocol. This could be because the  
16 effectiveness of an end of list cue is increased if features in the more richly encoded recency items have not at  
17 test been subject to interference from the silently generated recalled prior items.

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33 More recently, the so-called Revised Feature Model (Cyr, Poirier, Yearsley, Guitard, Harrigan, & Saint-Aubin,  
34 2022; Gionet, Guitard & Saint-Aubin, 2022; Saint-Aubin, Poirier, Yearsley, Robichaud, & Guitard, 2023)  
35 accounts for the production effect in IFR and ISR by similarly assuming that read aloud items are encoded with  
36 more features than visual silent items. Unlike the original Feature Model, it assumes that the overwriting effects  
37 are spread over a number of prior items, allowing for extended recency effects. More importantly, it also  
38 assumes that early list items benefit from rehearsal – as we suggested for our start-sequences – and further  
39 assumes that rehearsal is impeded by reading aloud the list items, giving rise to inverse modality effects (the  
40 recall advantage of visual items on earlier list items, Beaman, 2002; Grenfell-Essam, Ward & Tan, 2017;  
41 Macken, Taylor, Kozlov, Hughes, & Jones, 2016).

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53 A final starting point would be based on the perceptual-gestural framework advocated by Jones and colleagues  
54 (Jones & Macken, 2018; Jones, Hughes & Macken, 2006; Jones, Macken & Nicolls, 2004). The key defining  
55 feature of this approach is the suggestion that verbal short-term memory phenomena should be reconceptualised  
56 as perceptual objects subject to control processes directed towards particular goals. This approach has much in  
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3 common with other, neuroimaging-inspired, considerations that working memory might comprise a reactivation  
4 of the original perceptual representations of the objects maintained in a coherent form and distinct from ongoing  
5 perception by frontal lobe control processes. In our terms, a sequence (either a start-sequence or an end-  
6 sequence) could be such a perceptual object, with the goals defined by the experimenter-given instructions and  
7 the control processes counting start- and end- retrieval cues (and random guessing) within their number. Once  
8 again, an articulatory-rehearsal process is common to both – appearing within the Jones and Macken (2018)  
9 framework as a gestural component. Where we differ from Jones and Macken (2018) is in their rejection of the  
10 language of traditional concepts such as memory and forgetting – whether or not an end-sequence is best viewed  
11 as a perceptual object, it should be firmly embedded within – and relatable to – episodic (long-term) memory in  
12 order to speak to the voluminous literature on this task.  
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### 24 **Summary and Conclusion**

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26 In this article, we have argued that the WMM should be extended from ISR to IFR. We have reviewed prior  
27 evidence that suggests that ISR and IFR tasks are more similar than once thought, including that the two tasks  
28 are similarly affected by speech-based, Phonological Loop variables. We discussed some of the dilemmas faced  
29 by the WMM in addressing an integration of ISR and IFR. Although the WMM appears well-placed to explain  
30 the effects of speech-based factors and rehearsal in the two tasks, there remains uncertainty as to how the WMM  
31 accounts for recency effects and modality effects, how the WMM interacts with episodic long-term memory,  
32 and how the WMM accounts for serial position effects. In our new analyses, we have shown that the output  
33 orders in both IFR and ISR contain important runs of consecutively presented items that initiate with the first  
34 list item (start-sequences) and culminate with the last list item (end-sequences). We believe that end-sequences  
35 and recency effects, more generally, are under-appreciated in many theories of ISR, whereas the generation of  
36 start-sequences and primacy effects, more generally, are under-appreciated in many theories of IFR. Moreover,  
37 we argue that a knowledge of start- and end-sequences may be sufficient to constrain the location of other words  
38 recalled, such that plausible error transposition gradients may be generated without recourse to further serial  
39 position information, a finding that may reduce the difficulties for theories of IFR to be extended to ISR data.  
40 Thus, we believe that the WMM would benefit from embracing these issues, broadening its scope in explaining  
41 a wider range of immediate memory tasks and phenomena, and specifying the relationship between WMM and  
42 episodic long-term memory.  
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3 Finally, one of the reviewers of this paper questioned how our analyses inform the functionality of memory.  
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5 That is, using Baddeley's (1988) phrase, there must be something a memory system is "for". Although highly  
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7 speculative, we believe that the functionality (and intuitive appeal) of the WMM could only be further increased  
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9 by more fully integrating recency effects (including end-sequences): it is self-evidently important to situate  
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11 events in context, and to have heightened accessibility to what has recently occurred in particular contexts (at a  
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13 range of timescales). It is possible that start-sequences may assist with speech- and motor-planning, which when  
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15 combined with phonological awareness and development could be used in speech and language comprehension  
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17 and production, or vocabulary learning device (Baddeley et al., 1998). Thus, the WMM in general and the  
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19 Phonological Loop in particular would benefit from being extended to IFR (and other immediate memory  
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21 tasks), would benefit from a greater acknowledgement of the role of recency (and modality) in the two tasks,  
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23 and would benefit from a more precisely defined relationship between working memory and episodic long-term  
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25 memory in immediate memory tasks.  
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### 28 **Supplementary Material**

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30 The Supplementary Material is available at: [qjep.sagepub.com](http://qjep.sagepub.com)  
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## Figure Captions

Figure 1. From top to bottom, comparison of the effects of Phonological Similarity (PS), Articulatory Suppression (AS), Word Length (WL) and irrelevant speech (IS) on Immediate serial recall (ISR, left hand panels) and Immediate Free Recall (IFR, right-hand panels). The phonological similarity data and articulatory suppression data are generated from data from Spurgeon, Ward, and Matthews (2014, Experiments 2a, 2b) and Spurgeon, Ward, and Matthews (2014, Experiment 1), respectively. The word length data are adapted with permission from Figure 7 of Bhatarah, P., Ward, G., Smith, J., & Hayes, L. (2009). Examining the relationship between free recall and immediate serial recall: Similar patterns of rehearsal and similar effects of word length, presentation rate, and articulatory suppression. *Memory & Cognition*, 37(5), 689–713. The irrelevant speech/sound data are adapted with permission from Beaman, C. P., & Jones, D. M. (1998). Irrelevant sound disrupts order information in free recall as in serial recall. *The Quarterly Journal of Experimental Psychology: Section A*, 51, 615-636.

Figure 2. Figure adapted with permission from Figures 12 and 13 of Grenfell-Essam, R., & Ward, G. (2012).

Examining the relationship between free recall and immediate serial recall: The role of list length, strategy use, and test expectancy. *Journal of Memory and Language*, 67(1), 106–148. Serial position curves for lists of between 2 and 12 words presented for immediate free recall (IFR, top panels) and immediate serial recall (ISR, lower panels). The left-hand panels show data for participants who always knew the method of testing before encoding; the right-hand panels show data for participants who only knew the method of testing after encoding, immediately prior to retrieval.

Figure 3. Data from Grenfell-Essam and Ward (2012, Experiment 3) using start-end scoring. A word is only scored as correct if it is output as part of a start-sequence (a run of consecutive recalls starting with the first presented word) or as part of an end-sequence (a run of consecutive recalls ending with the last presented word).

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3 Figure 4. Data from Grenfell-Essam and Ward (2012, Experiment 3) plotting the proportion of words that were  
4 recalled that were not in a start-sequence or an end-sequence. These data have been recency-justified,  
5 such that more recent serial positions are aligned to the right of the panels,  
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11 Figure 5. Data from Osth and Dennis (2015). The proportion of words that were correctly recalled as part of a  
12 start-sequence (Panel 5A) or end-sequence (Panel 5B) when the completely correctly recalled sequences  
13 were included. The proportion of words that were correctly recalled as part of a start-sequence (Panel  
14 5C) or end-sequence (Panel 5D) when the completely correctly recalled sequences were excluded.  
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21 Figure 6. Data from Osth and Dennis (2015). The proportions of words presented at each serial position (SP)  
22 recalled at Output Positions 1 to 6. The peaks in each distribution show that words were most often  
23 recalled in the correct order.  
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29 Figure 7. Data from Osth and Dennis (2015). The proportion of order errors in the Observed data (Left hand  
30 panels) and the Estimated data (right-hand panels). The only serial position information assumed in the  
31 Estimated data is that inferred from start- and end-sequences.  
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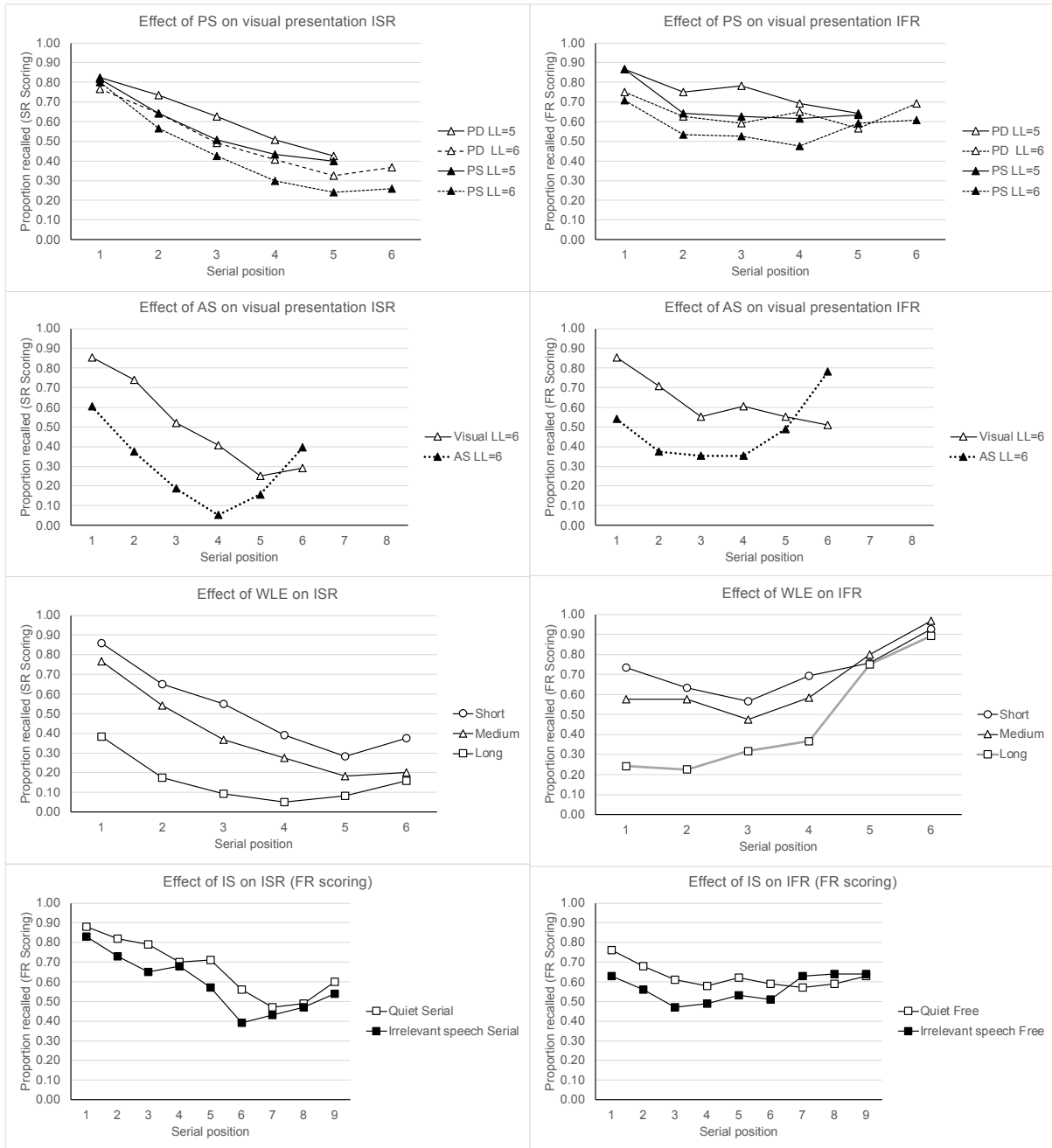


Figure 1.

Note: PS refers to Phonological Similarity (Phonologically-similar, PS and Phonologically-dissimilar, PD), AS refers to Articulatory Suppression (visual AS and visual silent), WL refers to Word Length (WL, short, medium and long words) and IS refers to Irrelevant Speech/Sound (Quiet, IS) on Immediate serial recall (ISR, left hand panels) and Immediate Free Recall (IFR, right-hand panels). LL refers to a specific List Length (selected from a wide range).

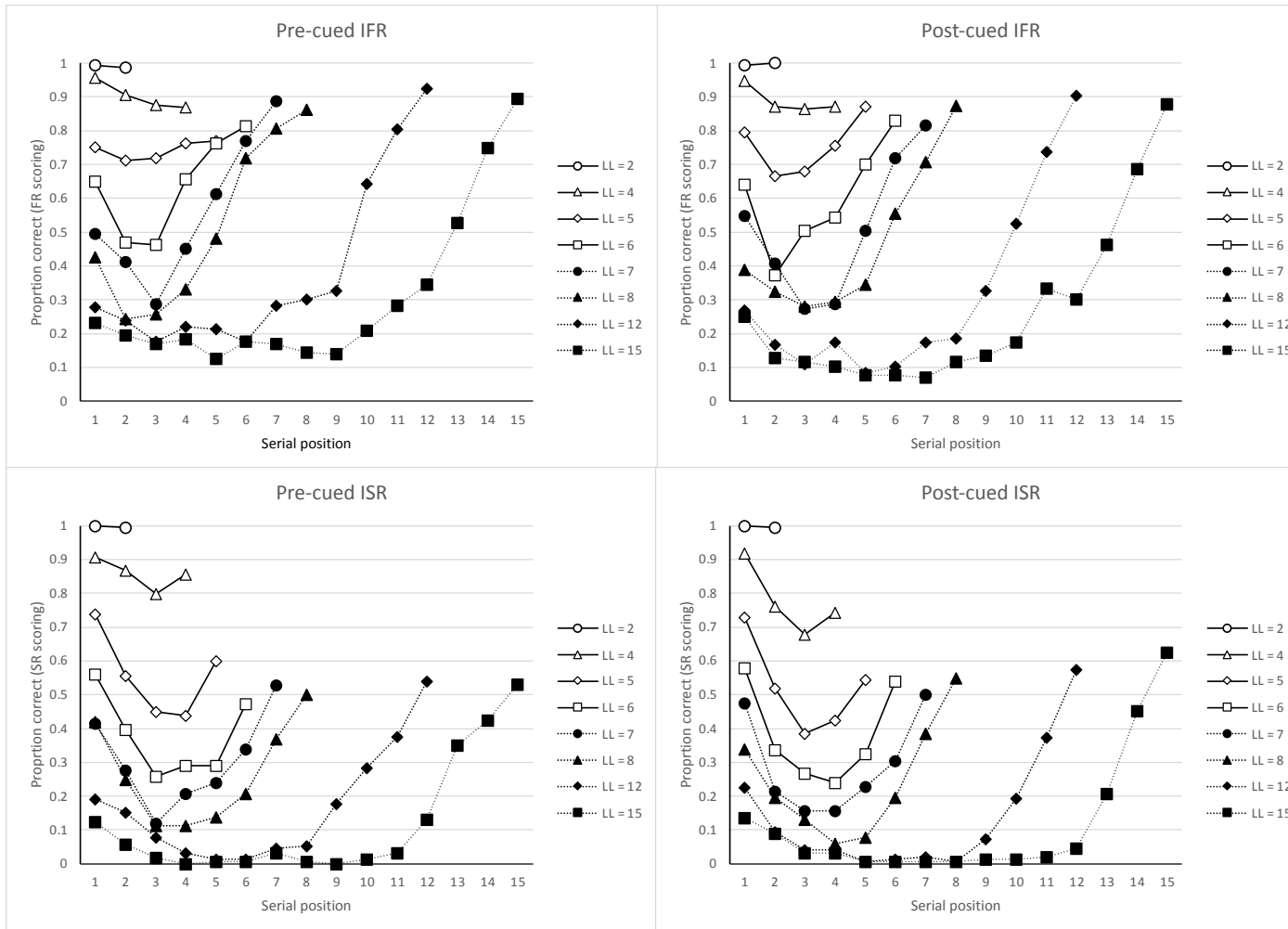


Figure 2. Data from Grenfell-Essam and Ward (2012, Experiment 3). Figure adapted from Grenfell-Essam, R., & Ward, G. (2012). Examining the relationship between free recall and immediate serial recall: The role of list length, strategy use, and test expectancy. *Journal of Memory and Language*, 67(1), 106–148.

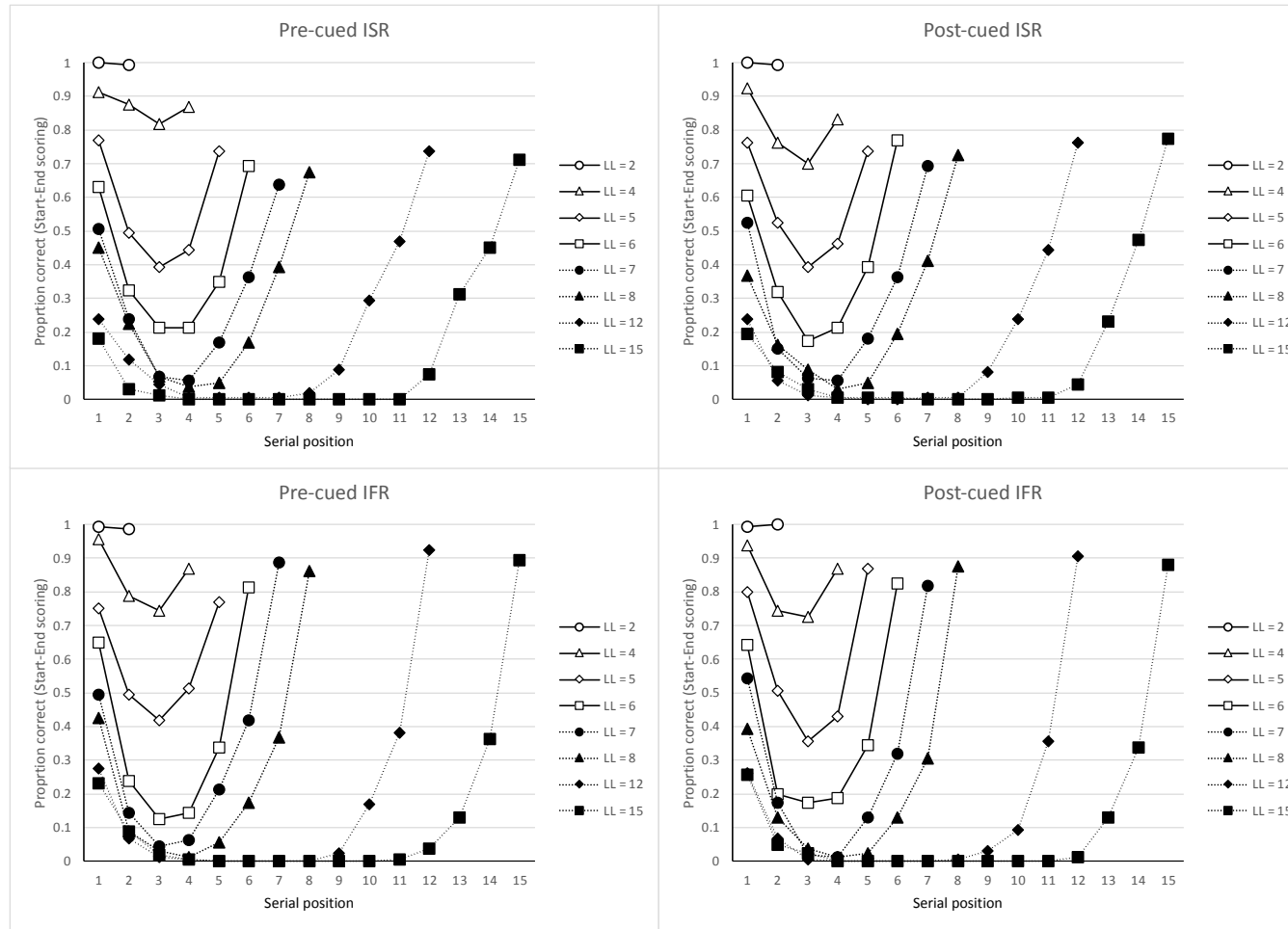


Figure 3. Data from Grenfell-Essam and Ward (2012, Experiment 3) using start-end scoring. A word is only scored as correct if it is output as part of a start-sequence (a run of consecutive recalls starting with the first presented word) or as part of an end-sequence (a run of consecutive recalls ending with the last presented word).

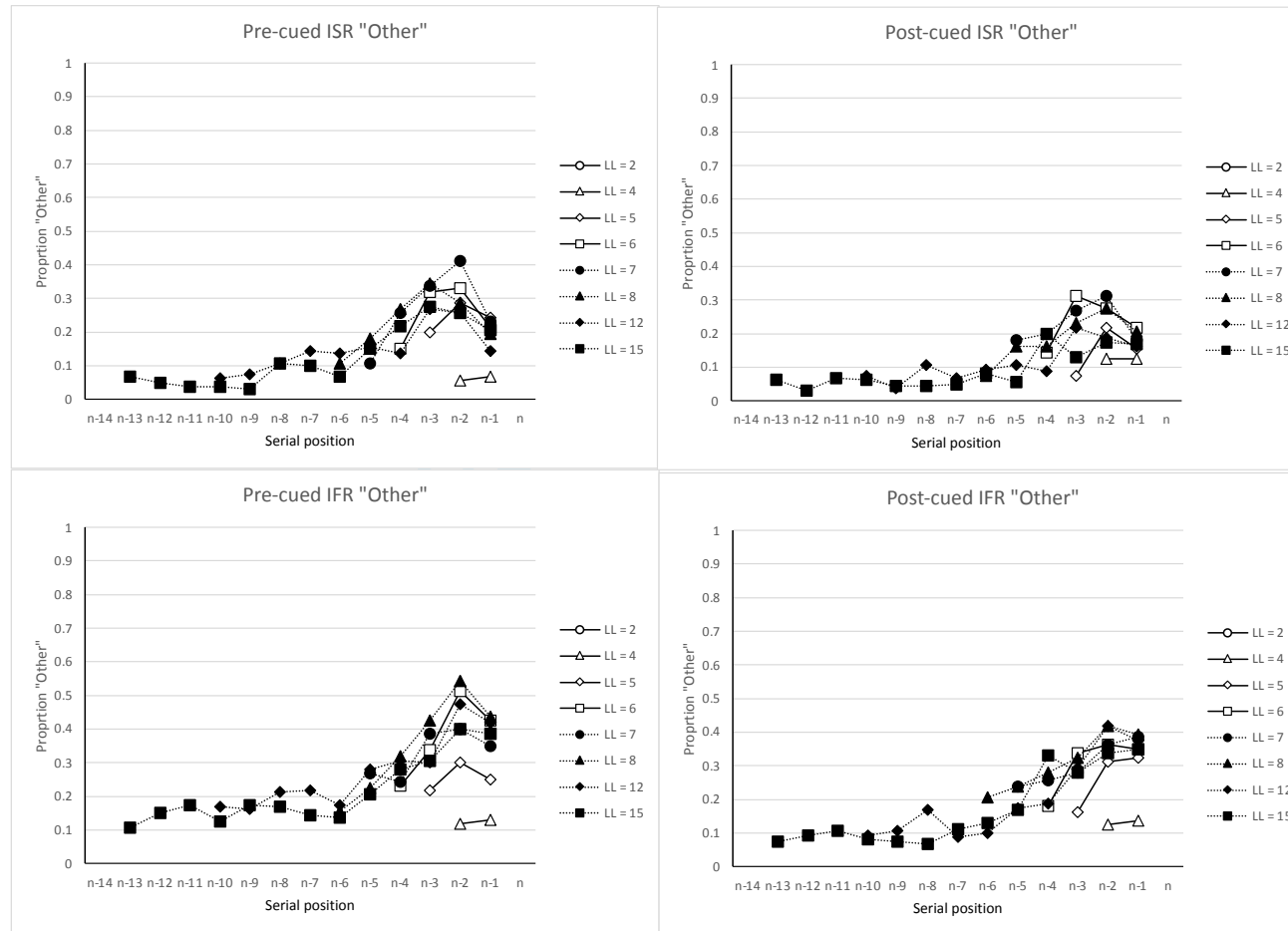


Figure 4. Data from Grenfell-Essam and Ward (2012, Experiment 3) plotting the proportion of words that were recalled that were not in a start-sequence or an end-sequence.

These data have been recency-justified, such that more recent serial positions are aligned to the right of the panels.



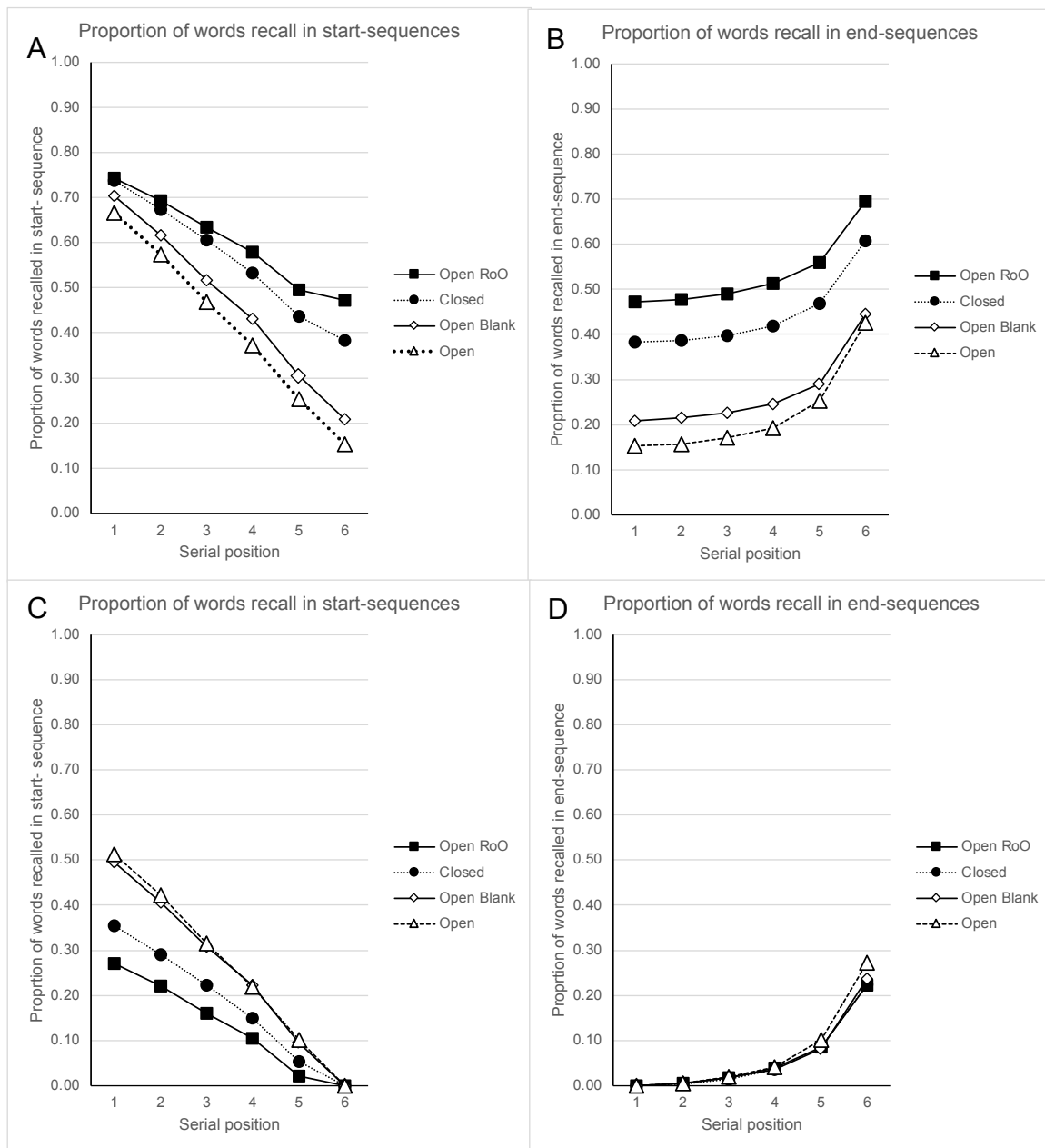


Figure 5. Data from Osth and Dennis (2015). The proportion of words that were correctly recalled as part of a start-sequence (Panel 5A) or end-sequence (Panel 5B) when the completely correctly recalled sequences were included. The proportion of words that were correctly recalled as part of a start-sequence (Panel 5C) or end-sequence (Panel 5D) when the completely correctly recalled sequences were excluded.

Note: ISR refers to Immediate Serial Recall; RoO refers to Reconstruction of Order. In the Open, Open Blanks and RoO groups, six new words were sampled without replacement on each trial. In the closed, six words from the stimulus set were randomly sampled without replacement on the first trial, and then repeatedly reshuffled on all subsequent trials. In the Open Blanks condition, participants were encouraged to type “blank” to indicate an omission.

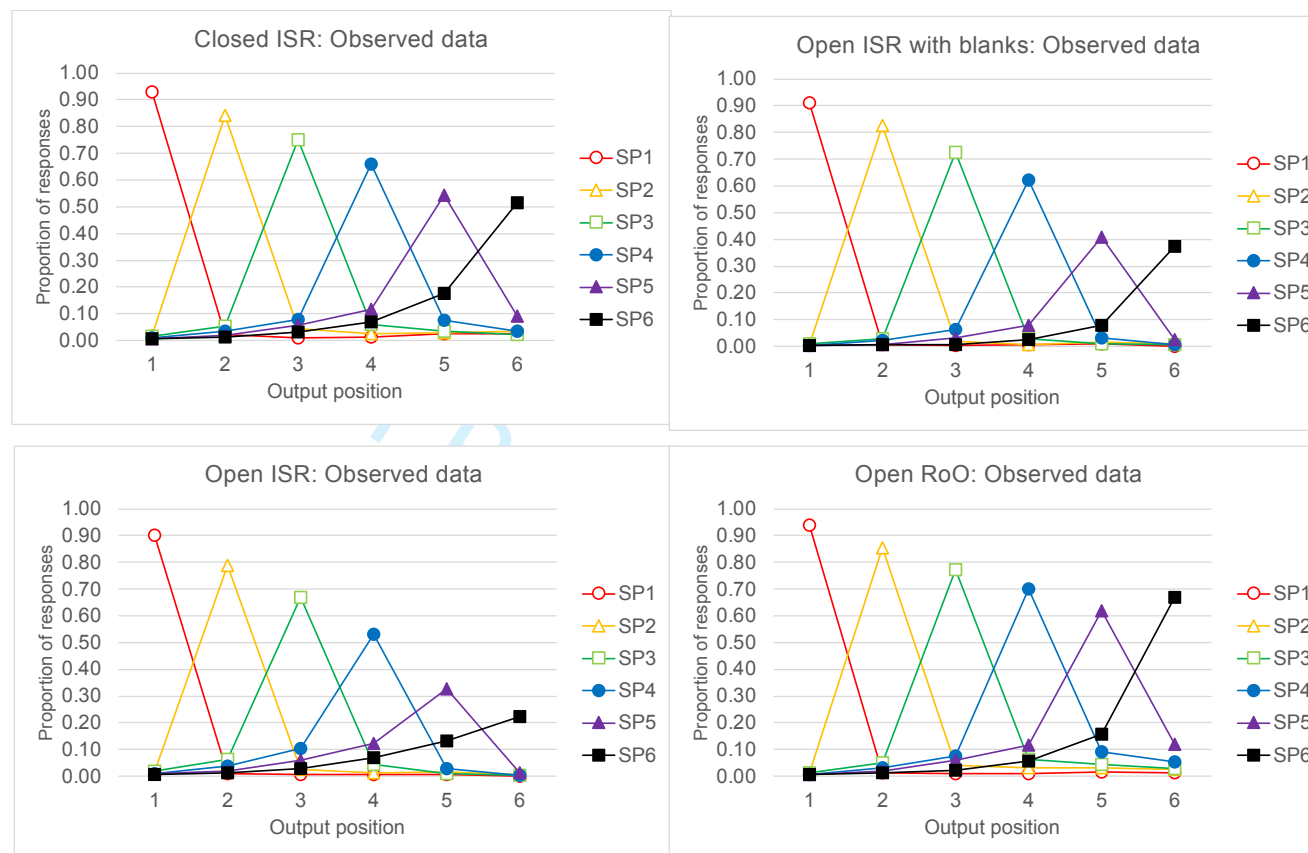


Figure 6. Data from Osth and Dennis (2015). The proportions of words presented at each serial position (SP) recalled at Output Positions 1 to 6. The peaks in each distribution show that words were most often recalled in the correct order.

Note: ISR refers to Immediate Serial Recall; RoO refers to Reconstruction of Order. In the Open, Open Blanks and RoO groups, six new words were sampled without replacement on each trial. In the closed, six words from the stimulus set were randomly sampled without replacement on the first trial, and then repeatedly reshuffled on all subsequent trials. In the Open Blanks condition, participants were encouraged to type “blank” to indicate an omission.

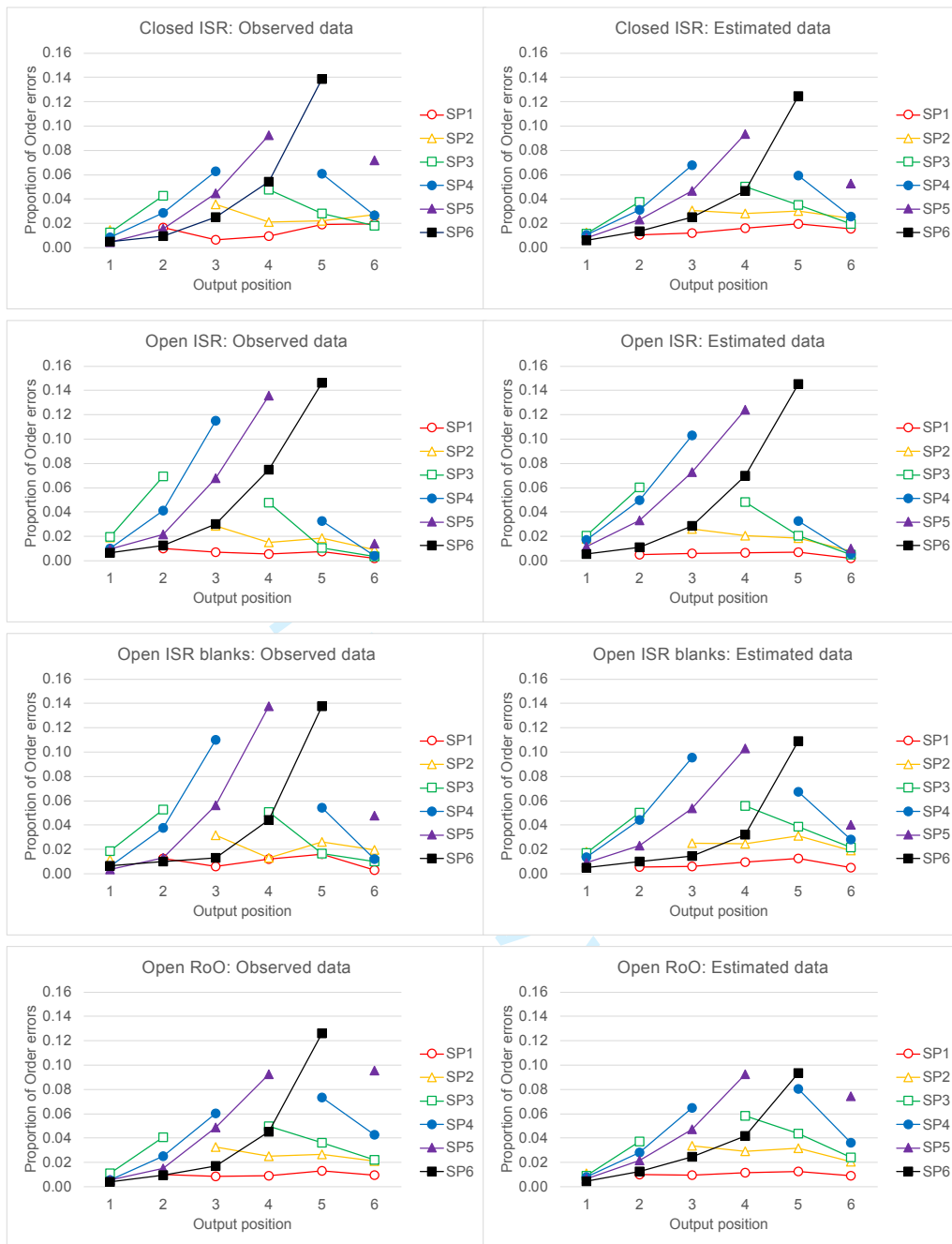


Figure 7. Data from Osth and Dennis (2015). The proportion of order errors in the Observed data (Left hand panels) and the Estimated data (right-hand panels). The only serial position information assumed in the Estimated data is that inferred from start- and end-sequences.

Note: ISR refers to Immediate Serial Recall; RoO refers to Reconstruction of Order. In the Open, Open Blanks and RoO groups, six new words were sampled without replacement on each trial. In the closed, six words from the stimulus set were randomly sampled without replacement on the first trial, and then repeatedly reshuffled on all subsequent trials. In the Open Blanks condition, participants were encouraged to type “blank” to indicate an omission.

Table 1

Immediate serial recall (ISR) data of Osth and Dennis (2015). The frequency distribution of sequences of recalls containing different combinations of start- and end-sequences.

| Group      | Length of Start-sequence | Length of End-Sequence |         |          |           |            |             |
|------------|--------------------------|------------------------|---------|----------|-----------|------------|-------------|
|            |                          | no end                 | end "6" | end "56" | end "456" | end "3456" | end "23456" |
| Closed ISR | no start                 | 232                    | 83      | 39       | 20        | 31         | 25          |
|            | start "1"                | 392                    | 135     | 74       | 52        | 31         | 0           |
|            | start "12"               | 412                    | 171     | 97       | 58        | 2          |             |
|            | start "123"              | 448                    | 211     | 93       | 0         |            |             |
|            | start"1234"              | 588                    | 244     | 5        |           |            |             |
|            | start "12345"            | 331                    | 7       |          |           |            |             |
|            | start "123456"           | 2347                   |         |          |           |            |             |
| Open ISR   | no start                 | 377                    | 86      | 50       | 31        | 30         | 30          |
|            | start "1"                | 569                    | 171     | 60       | 32        | 60         | 0           |
|            | start "12"               | 654                    | 209     | 95       | 69        | 0          |             |
|            | start "123"              | 595                    | 190     | 163      | 1         |            |             |
|            | start"1234"              | 733                    | 405     | 5        |           |            |             |
|            | start "12345"            | 626                    | 0       | 2        |           |            |             |
|            | start "123456"           | 943                    |         |          |           |            |             |
| Blanks     | no start                 | 367                    | 84      | 34       | 17        | 19         | 38          |
|            | start "1"                | 542                    | 112     | 40       | 26        | 51         | 1           |
|            | start "12"               | 612                    | 159     | 65       | 75        | 0          | 1           |
|            | start "123"              | 529                    | 179     | 139      | 1         | 1          |             |
|            | start"1234"              | 793                    | 427     | 1        |           |            |             |
|            | start "12345"            | 589                    | 2       |          |           |            |             |
|            | start "123456"           | 1294                   |         |          |           |            |             |
| Open RoO   | no start                 | 197                    | 63      | 26       | 23        | 19         | 31          |
|            | start "1"                | 286                    | 134     | 79       | 74        | 50         | 0           |
|            | start "12"               | 349                    | 196     | 111      | 34        | 0          |             |
|            | start "123"              | 321                    | 270     | 49       | 1         | 3          |             |
|            | start"1234"              | 485                    | 117     | 4        |           |            |             |
|            | start "12345"            | 127                    | 8       | 1        |           |            |             |
|            | start "123456"           | 2739                   |         |          |           |            |             |

Note: ISR refers to Immediate Serial Recall; RoO refers to Reconstruction of Order. In the Open, Blanks and RoO groups, six new words were sampled without replacement on each trial. In the closed group, six words from the stimulus set were randomly sampled without replacement on the first trial, and then repeatedly reshuffled on all subsequent trials. In the Blanks condition, participants were encouraged to type "blank" to indicate an omission.