First things first:

Similar list length and output order effects for verbal and non-verbal stimuli

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Running header: immediate free recall of verbal and non-verbal stimuli

Abstract

When participants are presented with a short list of unrelated words and they are instructed that they may recall in any order, they nevertheless show a very strong tendency to recall in forward serial order. Thus, if asked to recall *in any order*: "hat, mouse, tea, stairs", participants often respond "hat, mouse, tea, stairs" even though there was no forward order requirement of the task. In four experiments, we examined whether this tendency is language-specific, reflecting mechanisms involved with speech perception, speech production, and / or verbal short-term memory. Specifically, we examined whether we would observe similar findings when participants were asked to recall, in any order, lists of between 1 and 15 non-verbal stimuli, such as visuo-spatial locations (Experiment 1, Experiment 3, Experiment 4), or touched facial locations (Experiment 2). Contrary to a language-specific explanation, we found corresponding tendencies (albeit somewhat reduced) in the immediate free recall of these non-verbal stimuli. We conclude that the tendency to initiate recall of a short sequence of items with the first item is a general property of memory, which may be augmented by verbal coding.

183 words

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Recently, Ward, Tan, and Grenfell-Essam (2010) reported the first systematic investigation into an experimental finding that was first reported by Corballis (1967) and then again by Neath and Crowder (1996). When participants are asked to recall a short list of words *in any order,* such as: "hat, mouse, tea, stairs", they often respond in forward serial order (that is, they recall "hat, mouse, tea, stairs"), even though there was no forward order requirement of the task. Ward *et al*. argued that this finding was important for two reasons. First, the finding encouraged greater theoretical integration between the otherwise divergent immediate free recall (IFR) and immediate serial recall (ISR) literatures. Second, the finding is potentially difficult to explain by many theories of IFR that emphasize the importance of explaining recency effects (that is, the high accessibility of items presented toward the end of a list). Third, the finding adds to the growing body of evidence that suggests that forward-ordered recall may be a defining principle of episodic memory (e.g., Hurlstone, Baddeley, & Hitch, 2014).

One specific aim of the current work is to address the question of whether this forward-ordered tendency observed in the IFR of verbal stimuli reflects the operation of language-specific mechanisms (such as a speech input/output buffer or a verbal short-term memory system) or whether the tendency is a more general property of memory that can also be observed across different (non-verbal) materials. A second more general aim of the current work is to examine the functional similarities and differences between IFR of stimuli from verbal and non-verbal domains.

In the introduction that follows, we outline more fully the phenomenon of interest, we discuss why it is important, and we consider the somewhat limited evidence supporting language-specific explanations of the phenomenon, such as verbal rehearsal, a phonological short-term store, and a short-term verbal buffer memory. Finally, we review related evidence from the visuo-spatial memory literature to determine whether we might expect analogous findings when a language-specific explanation can be discounted.

The Phenomenon of Interest

Ward *et al*. (2010) presented participants with lists of between 1 and 15 words, one at a time, and at the end of the list, the participants were required to recall as many words as they could either in strict forward serial order (ISR) or in whatever order that they wished (IFR). Although previous research had often treated the data and theories associated with the two tasks somewhat separately, Ward *et al*. showed that the output order and the serial position curves for the two tasks were far more similar than one might have expected once the list lengths, methodology, and scoring systems were equated (for further evidence and discussion, see Bhatarah, Ward, Smith & Hayes, 2009; Grenfell-Essam & Ward, 2012).

The critical observation for this research was that when participants were presented with a short list of words for IFR, they often recalled the list in an "ISR-like" manner, even though they were free to recall in whatever order they so wished. The tendency to initiate recall with the first list item was greatest for short lists, and it decreased with increasing list length. Furthermore, when recall started with the first list item, participants tended to continue to recall other earlier items, often in a forward serial order, resulting in extended *primacy effects* (the recall advantage for earlier list items).

By contrast, at longer list lengths, there was a tendency for participants to initiate recall with one of the last four list items, and this complementary tendency increased with increasing list length. When recall started with one of the last four list items, participants tended to recall other later items, resulting in extended *recency effects* (the recall advantage for later list items).

The Importance of the Phenomenon

The heightened accessibility to the first list item in a short list is somewhat surprising given that explanations of recency effects have dominated theoretical accounts of IFR. Much of the theoretical debate in the last 40 years has concerned whether the recency effects in IFR reflect the contents of a separate short-term memory store (STS). Early dual-store accounts of IFR assumed that an STS underpinned all recency and retrieval from the long-term memory store (LTS) was insensitive to recency (e.g., Atkinson & Shiffrin, 1971; Glanzer, 1972; Raaijmakers & Shiffrin, 1981). These accounts had difficulty in accounting for the persistence of recency effects when the contribution of an STS was minimized, such as the recall of real-world events over long periods of time (e.g., Baddeley & Hitch, 1977; Pinto & Baddeley, 1991; Rubin, 1982), or the recall of words in the laboratory-based continuous distractor free recall task, in which a filled distractor interval that is assumed to overwrite the contents of STS is inserted immediately after each word in the list (e.g., Bjork & Whitten, 1974; Glenberg, *et al*., 1980; Howard & Kahana, 1999, for reviews, see Crowder, 1993; Greene, 1986, 1992).

Observing recency effects across a wide range of time-scales has encouraged theorists to propose unitary memory accounts that assume common mechanisms for the encoding, storage, and retrieval of all the list items (e.g., Brown, Neath & Chater, 2007; Howard & Kahana, 2002; Laming, 2006, 2008, 2009; Polyn, Norman & Kahana, 2009; Sederberg, Howard & Kahana, 2008; Tan & Ward, 2000). These theories assume that the most recent items are more temporally distinct (Brown *et al*., 2007; Glenberg & Swanson, 1986), or are associated with temporal contexts that are more similar to the end of list (Howard & Kahana, 2002; Polyn, Norman & Kahana, 2009; Sederberg, Howard & Kahana, 2008; Tan & Ward, 2000; Ward, 2002; Ward & Tan, 2004) than earlier list items.

Currently, most theorists accept that some long-term recency mechanism is required, but there remains on-going controversy as to whether the recency effects in IFR necessitate both short-term and long-term recency mechanisms, with some theorists proposing a dichotomy (e.g., Davelaar, Goshen-Gottstein, Ashkenazi, Haarman & Usher, 2005; Davelaar, Usher, Haarmann, & Goshen-Gottstein, 2008; Farrell, 2010; Lehman & Malmberg, 2013; Raaijmakers, 1993; Thorn & Page, 2008; Unsworth & Engle, 2007; Usher, Davelaar, Haarmann, and Goshen-Gottstein, 2008) whilst others appeal to the unitary view (e.g., Howard, Kahana, & Sederberg, 2008; Kahana, Sederberg, & Howard, 2008; Neath & Brown, 2006; Surprenant & Neath, 2009).

Language-specific explanations of the phenomenon

The discovery that participants tend to perform IFR of a short list of words in an "ISR-like" manner is therefore particularly surprising, and as Ward *et al*. (2010) argued, it is particularly difficult for unitary accounts that might otherwise predict that the first item recalled would be one of the most recent items (rather than the first item). Rehearsal is often invoked to explain primacy effects within recency-based accounts of IFR (e.g., Tan & Ward, 2000), but Grenfell-Essam, Ward, and Tan (2013) have recently shown that the tendency to initiate recall with the first list item in short lists in IFR was unlikely to be mediated by rehearsal. They showed that doubling the presentation rate from 1 word / s to 2 words / s did not affect the probability of first recall data. Moreover, they additionally showed that the ISR-like tendency was also observed (albeit at a reduced extent) when participants were prevented from rehearsal by requiring them to articulate repeatedly an irrelevant word (e.g., "the, the, the…"), a manipulation referred to as *articulatory suppression* (AS).

An alternative possibility is that "dual-store" models of IFR are better placed to explain the Ward *et al*. data. Although short-term memory is normally associated with superior recall of the last few list items in IFR, one could plausibly imagine that if the list length was short enough, then a short-term memory store might maintain the first few list items prior to immediate recall. Indeed, one might argue that the "ISR-like recall" of a short list in a test of IFR could represent a more distinct signature of verbal short-term memory than the enhanced recency effects in IFR of long lists. Certainly, the "ISR-like" pattern of recall observed with short lists is difficult to account for using general temporal distinctiveness or a general temporal context mechanism that predict enhanced recency effects.

Recent examinations of a verbal STS explanation of the phenomenon have led to somewhat mixed findings. First, Spurgeon, Ward, and Matthews (in press) have examined the effect of a filled distractor period on the free recall of words of different list lengths. Specifically, they examined the immediate, delayed, and continual distractor free recall of between 1 and 12 words. They found that the tendency to initiate recall with the first list item was present (albeit at a reduced rate) in the delayed free recall and CDFR conditions, suggesting that the tendency to initiate recall with the first list item may be enhanced in an immediate test, but the finding does not *necessitate* access to a verbal short-term store.

Second, Spurgeon, Ward, and Matthews (2014) considered the extent to which IFR and ISR were supported by a phonological short-term store (e.g., the Phonological Loop, Baddeley 1986; 2000; 2007; 2012), and examined whether the loop was responsible for the tendency to initiate recall of short lists of words with the first list item. The Phonological Loop was posited by Baddeley and Hitch (1974) as a limited-capacity, short-term memory store capable of maintaining short sequences of speech-based information in serial order. Items within the loop are assumed to decay with time unless they are refreshed through rehearsal. The loop was fractionated into two components (Baddeley, 1986), a phonological store and an articulatory rehearsal process. According to the Working Memory model (Baddeley, 1986), spoken words are assumed to enter the phonological store automatically, but written words enter the phonological store only if they have been phonologically recoded (covertly or overtly). Critically, if participants are required to perform AS then participants are not only prevented from rehearsal, but they cannot recode written words into the phonological store. The Phonological Loop has been argued to support language learning (e.g., Gathercole & Baddeley, 1989), and language clearly has an intrinsic forward ordered requirement. One might imagine that the Phonological Loop maintained short lists of words for both IFR and ISR in a forward serial order, but at longer list lengths the early items may be overwritten or displaced by later list items. Spurgeon *et al*. examined IFR and ISR under conditions in which the Phonological Loop is assumed to be used (visual No AS conditions) as well as conditions that are assumed to prevent the phonological recoding of items into the Phonological Loop (visual AS conditions). Consistent with the Working Memory model, a phonological similarity effect provided evidence of phonological recoding of the visually presented words only in the No AS condition and not when the words were presented under AS. However, the tendency to initiate IFR with the first list item was not sensitive to phonological similarity and was still present (albeit at a reduced rate) in the visual AS condition, suggesting that the tendency to initiate IFR with the first list item may be *augmented* by phonological recoding but does not *necessitate* access to the Phonological Loop.

These two recent studies suggest that the tendency to initiate recall of a short list with the first item might not necessitate a (phonological) short-term store, but rather the tendency may be a general property of memory that operates across different modalities of presentation and across different timescales. In this research, we test the generality of the finding still further and seek to rule out the necessity of a language-specific mechanism (such as speech input or a speech output buffers, verbal short-term memory) by examining whether the Ward *et al*. (2010) findings could also be observed in the IFR of non-verbal material.

The immediate memory of non-verbal items

A language –specific mechanism of the phenomenon could be tested if one examined whether similar findings were observed in the IFR of non-verbal stimuli. Early research comparing verbal and visuo-spatial immediate memory suggested that the two stimulus domains were underpinned by very different mechanisms. Verbal short-term memory was commonly assessed by immediate serial recall (ISR), which resulted in bowed serial position curves showing extended primacy and limited recency (e.g., Drewnowski & Murdock, 1980). By contrast, visual short-term memory was commonly assessed by two alternative forced-choice (2AFC) recognition tests, which resulted in no primacy and 1-item recency (e.g., Broadbent & Broadbent, 1981; Phillips, 1983; Phillips & Christie, 1977a, 1977b). These distinctions contributed to the proposal of separate short-term memory stores for verbal and visuo-spatial information with very different capacities and capabilities, such as the phonological loop and the visuo-spatial sketchpad in the highly influential Working Memory model (Baddeley, 1986, 2000, 2007, 2012; Baddeley & Hitch, 1974; Baddeley &

Logie, 1999; Logie, 1995). Consistent with separate modality-specific memory stores, early evidence from dual-task studies (e.g., Farmer, Berman, & Fletcher, 1986) confirmed that the short-term retention of verbal information was selectively interfered with by verbal rather than spatial secondary task, whereas the short-term retention of spatial information was selectively affected by a spatial rather than verbal secondary task.

However, Smyth and Scholey (1996) and Jones, Farrand, Stuart, and Morris (1995) have shown bowed serial position curves when participants were presented with a sequence of different visuo-spatial locations and were then asked to recall the sequence by pointing at the locations in the same serial order as they had been presented. Furthermore, when participants were presented with a sequence of hard-to-name visual stimuli (such as a series of unfamiliar faces or visuo-spatial matrices) and were then re-presented with all the stimuli at different positions on the screen, participants showed bowed serial position curves in their ability to select the items in the order in which they had been presented (the *reconstruction of order task*, Avons, 1998; Avons & Mason, 1999). Smyth, Hay, Hitch & Horton (2005) confirmed the presence of bowed serial position curves with non-verbal face stimuli, and showed that this pattern of performance was not removed by AS. This research suggests that early studies that used very different methodologies over-estimated the differences between verbal and non-verbal stimuli. Rather, the recall patterns observed across modalities appear more similar when more equivalent methodologies are used (e.g., Farrand, Parmentier, & Jones, 2001; Ward, Avons, & Melling, 2005).

Guérard and Tremblay (2008) further confirmed similarities in the patterns of correct performance and patterns of errors when they compared the serial recall of verbal and spatial memory. They presented participants with sequences of seven words (verbal stimuli) or sequences of seven circles (spatial stimuli). There were two tests of serial order for each type of stimulus. A serial recall test in which participants wrote down the words or clicked on the screen to reproduce the sequence of stimuli, and a reconstruction of order test in which all the stimuli were re-displayed at test, and the participants selected the items in order by clicking on the represented stimuli using a computer mouse. They found that there were consistent similarities between verbal and spatial information in the patterns of correct recall and distribution of types of intrusions, transpositions, omissions and fill in errors for verbal and spatial stimuli in serial reconstruction of order tasks. Guérard and Tremblay (2008) also confirmed that verbal immediate memory was selectively interfered with by concurrent AS and spatial immediate memory was selectively interfered with by concurrent spatial interference (spatial tapping). Guérard and Tremblay (2008) therefore found evidence consistent with functional equivalence of serial recall (based on the patterns of serial recall data) at the same time as evidence for modularity (based on the patterns of dual task interference).

Moreover, in a recent review, Hurlstone *et al*. (2014) examined whether the serial recall of verbal, visual, and spatial memory could be underpinned by equivalent computational memory mechanisms. They argued that all short-term memories use a competitive queuing (CQ) mechanism in which candidate items are considered for output in parallel with the most activated item selected and output and subsequently suppressed. Hurlstone *et al*. argue that it is this common reliance on CQ that drives the similarities across domains. However, although serial order in the verbal short-term memory CQ system is assumed to be represented by a primacy gradient, position marking, response suppression and cumulative matching, and that item similarity and output interference also affect recall, Hurlstone *et al*. argued that it was currently unclear how serial order was represented within the nonverbal CQ systems, primarily because the relevant studies have not as yet been performed.

On the IFR of non-verbal items

In their review, Hurlstone *et al*. (2014) note that the importance of serial recall is underscored by the spontaneous forward ordered recall observed in IFR. The extension of the Ward *et al*. (2010) methodology from verbal to non-verbal stimuli (including visuo-spatial stimuli) will therefore not only determine whether the "ISR-like" patterns of IFR are limited to verbal lists (indicating a language-specific explanation for this finding) but will also inform the debate as to whether the recall of verbal and non-verbal memories are underpinned by similar or different memory mechanisms, and help evaluate the importance of forward ordered recall in non-verbal domains.

Somewhat surprisingly, we could only find two studies that have both examined the IFR of non-verbal stimuli. First, Bonanni, Pasqualetti, Caltagirone, and Carlesimo (2007) presented participants with a 5 x 5 grid of 25 squares, and during presentation, they saw sequences of 6, 8, and 10 squares that changed colour one at a time. Following the last presentation, participants were required to select the squares that had previously changed colour, in any order. Bonanni *et al*. (2007) observed both primacy and recency effects, with more pronounced recency effects at the longest list length. They also showed that an increase in the presentation rate results in stronger primacy effects.

More recently, Gmeindl, Walsh, and Courtney (2011) compared performance in a verbal digit span task and a computerized visuo-spatial Corsi-block task. In the first experiment, participants performed both ISR and IFR using digits and visuo-spatial locations as stimuli. Gmeindl *et al*. found an ISR advantage but an IFR disadvantage for the verbal relative to the spatial stimuli. Critically, although there were some “ISR-like” sequences reproduced in the IFR tasks for both stimulus types, these were over twice as common with verbal relative to the spatial stimuli. By contrast, participants tended to respond in the IFR spatial tasks in a way that reduced the inter-item distance between responses.

In Gmeindl *et al*.’s second experiment, the verbal superiority in memory for order was confirmed using a serial recognition task, in which participants were asked to detect any difference in the order of two sequences. Participants were again slightly better at ISR with verbal compared with visuo-spatial stimuli, and were more likely to detect a change in serial order with digits when compared to visuo-spatial locations. Gmeindl *et al*.’s preferred interpretation was that serial order was more readily bound to verbal rather than to visuo-spatial stimuli.

Although these two studies encourage the possibility that we might find "ISR-like" recall in non-verbal stimuli, it should be noted that the Bonnani *et al*. (2007) study showed some primacy in their IFR data, but did not report whether recall had occurred in forward serial order. The Gmeindl *et al*. data did show serial recall even in IFR of non-verbal stimuli, but because of the within-subjects design, there is the possibility that participants' strategy when performing the IFR of non-verbal stimuli was affected by the ISR strategies employed in earlier conditions. The use of only a limited number of stimuli that were repeated within a trial is also unusual in IFR, and the tendency to double-click any twice-presented visual-spatial stimuli might strongly affect the inter-item distances.

By contrast, the current experiments examined the IFR of non-verbal stimuli using many more list lengths, and the data are presented in far more detail. That is, for each list length and type of stimulus, we provide serial position curves, analyses of output orders, and consider the effects of the first word recalled on the shape of the subsequent serial position curves. Therefore, we believe that a major contribution of the current experiments is to provide a rich data set that is particularly informative in answering the question of whether verbal and non-verbal IFR involve similar or different recall processes.

Experiment 1

Experiment 1 examined whether the pattern of data reported by Ward *et al*. (2010) with lists of between 1 and 15 words would also be observed with sequences of between 1 and 15 visuo-spatial locations. On each trial, participants saw a different random set of 30 rectangles distributed across the two dimensions of the computer screen. Following a warning tone, a subset of between 1 and 15 rectangles then darkened one by one at a rate of 1 rectangle per second. The end of the list was signified by a further tone, after which participants were free to select the rectangles that had darkened by clicking on them in whatever order they liked.

Method

Participants. Twenty unpaid volunteer students from the University of Essex participated in this experiment.

Materials and Apparatus. The stimulus set consisted of 432 rounded rectangles arranged in 18 rows of 24 columns. Each rectangle was white with a black outline and measured 9mm x 8mm and they were distributed over a grey background display measuring 285 mm wide by 165 mm in height. On each trial, participants saw a different random subset of 30 of the rectangles. The experiment was presented via the Supercard application on an Apple Mac Computer, and participants interacted by clicking on selected rectangles using the computer mouse.

Design. The experiment used a within-subject design. There were two within-subjects independent variables: list length with 11 levels (1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 15 rectangles presented) and serial position with up to 15 levels. The dependent variables were the proportion of rectangles correctly recalled, the proportion of rectangles recalled in the same order as presented, the probability of initiating recall with the first or with one of the last four presented rectangles.

Procedure. Participants were tested individually and were given instructions and performed four practice trials in the presence of the experimenter, followed by two blocks each of 44 experimental trials. Within each block, there were 4 trials of each of the 11 different list lengths. The order of these trials within each block was randomised. Participants were encouraged to take a short break between the first and second blocks.

On each trial, participants were presented with a different random subset of 30 rounded rectangles that were distributed across a computer screen. After 1 second, there was a warning tone, and then a subset of between 1 and 15 of the rectangles darkened one at a time at a rate of 1 rectangle per second (where each white rectangle turned black for 0.75s with an additional 0.25s inter-stimulus interval where the item returned to its original colour). During the stimulus presentation, the location of the mouse cursor was locked to the location of the “submit” button near the top right-hand corner of the display.

An auditory cue signalled the start of recall, after which the mouse cursor could be moved, and the participants were free to indicate which rectangles had darkened by clicking on the chosen rectangles in whatever order they liked. The rectangles turned grey upon their selection and could not be selected twice on the same trial. It was also not possible to select more rectangles at test than had been presented. At the same time as the auditory cue to recall was presented, a pair of boxes appeared on the right hand side of the screen indicating the number of rectangles that had darkened on that trial and the number of items that had so far been selected. Participants could only use the "submit" button once they had selected as many rectangles at test as had been darkened. Pressing the "submit" button initiated the next trial.

Results

Overall accuracy. The open circles plotted in Figure 1A show the mean proportions of rectangles correctly selected at each of the 11 list lengths. A within-subjects analysis of variance (ANOVA) with one factor list length (with 11 levels, list lengths 1-8, 10, 12, and 15) revealed that there was a highly significant list length effect, $F(10, 190)=67.4$, $MSE = .006$, $\eta^2_p = .781$, $p < .001$. Pairwise comparisons of the main effect showed that the proportion of rounded rectangles that were accurately recalled decreased with increasing list length.

--Figure 1 about here--

Serial position curves. Figure 2A shows the serial position curves for the eleven different list lengths. Appendix A1 shows the results of the statistical analyses performed on the data at each list length. At short list lengths, IFR was very accurate and there were no serial position effects. At medium and long list lengths (specifically, list lengths 7, 10, 12 and 15), IFR was far less accurate and there were bowed serial position curves, with significant primacy and recency effects.

--Figure 2 about here--

Probability of First Recall (PFR). Figure 3A shows the mean probability for each list length that the first rectangle selected was (a) the first rectangle that was presented, (b) one of the last four rectangles that were presented, (c) any of the other rectangles that had been presented, or (d) a rectangle that had not been presented.

--Figure 3 about here--

The probability of initiating recall with the first list item decreased significantly as list length increased, $F(10, 190)=33.3$, $MSE = .036$, $\eta^2_p = .637$, $p < .001$. The probability of initiating recall with one of the last four rectangles increased significantly as list length increased, $F(9, 162)=6.08$, $MSE = .040$, $\eta^2_p = .252$, $p < .001$. The probability of initiating recall with any of the other rectangles increased significantly as list length increased, $F(10, 190)=5.37$, $MSE = .020$, $\eta^2_p = .220$, $p < .001$.The probability of initiating recall with an error did not increase significantly as list length increased, $F(10, 190)=1.42$, $MSE = .008$, $\eta^2_p = .070$, $p = .173$.

The effect of first recall on the serial position curves. Figure 4A shows the serial position curves for those trials in which recall initiated with serial position 1 (that is, when P(FR=SP1)) using free recall (FR) scoring. There are more extended primacy effects and reduced recency effects in this subset of data. Appendix B1 shows that these serial position effects reached significance at list lengths 5, 6, 12, and 15.

--Figure 4 about here--

Figure 4B shows the resultant serial position curves for data conditionalized by trials in which recall initiated with one of the last four serial positions (that is, when P(FR=Last 4)) using free recall (FR) scoring. It is clear that there are more extended recency effects and reduced primacy effects in this subset of data. Appendix C1 shows that these serial position effects reached significance at all lists of lengths 6 and greater.

Finally, Figure 4C shows the resultant serial position curves for data conditionalized by trials in which recall initiated with serial position 1 (that is, when PFR=SP1)) using serial recall (SR) scoring. It is clear that there are greatly extended primacy effects and little or no recency effects in this subset of data. Appendix D1 shows that these serial position effects reached significance at list lengths 5, 6, 7, 8, 12 and 15.

An analysis of output transitions using Lag-CRP curves. Figure 5A shows the Conditionalized Response Probabilities (CRPs) of the transitions between successive pairs of words that are recalled. In a lag-CRP curve, the lag between any successive pairs of recalled words is calculated by subtracting the serial position of the first word of the pair from the serial position of the second word of the pair. Small values of lag indicate that successive outputs were from very similar serial positions; larger lags indicate that successive outputs were from very different regions of the serial position curve. Positive lags indicate recall in a forward direction; negative lags represent outputs in a backward direction. A lag of +1 indicates that the output order of the pair of words was the same as the input order. The CRP is calculated by summing the total number of transitions of each lag made by each participant for every list length and then dividing this number by the total number of opportunities that that participant had to make such a transition (for full details, see e.g., Howard & Kahana, 1999; Kahana, Howard, & Polyn, 2008). Typically with lists of words, the Lag-CRP plots show asymmetric lag recency effects (e.g., Howard & Kahana, 1999; Kahana, 1996), such that there is a preference for transitions to nearer neighbors than remote neighbors and a general tendency to proceed in forward than a backward order. Figure 5A shows that the lag-CRP curves observed with the non-verbal stimuli in Experiment 1 clearly resemble those obtained from IFR of verbal lists.

--Figure 5 about here--

Discussion

Experiment 1 showed that the patterns of data observed when participants perform IFR with sequences of visuo-spatial locations are qualitatively similar to the patterns of data found in previous studies that have used words as stimuli. Replicating previous findings from verbal IFR (e.g., Jahnke, 1965; Murdock, 1962; Ward, 2002) and visuo-spatial IFR (Bonnani *et al*., 2007) there are clear list length effects with the visuo-spatial rectangles.

Critically, Experiment 1 showed that participants tended to initiate recall with the first item in the list when the list was short, but tended to increasingly initiate recall with one of the last four items in the list when the list length was increased, a finding mirroring that observed with words by Ward *et al*. (2010). In addition, different-shaped serial position curves were observed when the data were conditionalized by the first location recalled. Participants showed increased primacy and reduced recency when they started with serial position 1, and there was clear evidence of "ISR-like" recall with short lists when the same data were further examined using SR scoring. In addition, there was increased recency and reduced primacy when recall initiated with one of the last four serial positions. Furthermore, the Lag-CRP analysis of the output orders revealed that the transitions between successive outputs with IFR of non-verbal stimuli showed similar asymmetric lag recency effects to those typical with IFR of verbal list items.

These findings suggest that the Ward *et al*. findings observed with lists of words are not limited to language-specific mechanisms such as a speech input, speech output or verbal short-term memory, but reflect either general memory mechanisms or similar memory mechanisms operating in different domains (cf. Guérard & Tremblay, 2008; Hurlstone *et al*., 2014).

Experiment 2

Experiment 1 showed that the list length effects in IFR observed by Ward *et al*. (2010) with lists of words were also observed with sequences of visuo-spatial locations. In Experiment 2, we sought to generalize the findings still further to the sense of touch by determining whether the same patterns of data could be observed with sequences of touched facial locations. Far less research has been performed on tactile (Gallace & Spence, 2009; Katz, 1989; Picard & Monnier, 2009) compared with verbal memory, probably because of the greater difficulty of utilizing tactile stimuli in controlled experimental settings. As reviewed by Gallace and Spence (2014), a number of studies have sought to find evidence for people's memory for the location of touch.

Some studies have examined whether there are tactile sensory memories, using methods derived from the visual and auditory sensory memory literatures (i.e., iconic and echoic memories, respectively). These studies have examined the advantage in accuracy when participants are cued to recall only a subset of presented information (the partial report superiority effect, e.g., Bliss, Hewitt, Crane, Mansfield & Townsend, 1966; Gallace, Tan, Haggard, & Spence, 2008), the interaction between partial report advantage and cue delay (Gallace, *et al*., 2008), and the detrimental effect of an irrelevant suffix stimulus (Manning, 1978; Watkins & Watkins, 1978). These studies provide partial but not unequivocal evidence to support a tactile sensory memory.

Additional studies have examined evidence for tactile working memory, using methods more analogous to those used in short-term verbal memory tasks (e.g., Gilson & Baddeley, 1969; Miles & Borthwick 1996; Sullivan & Turvey 1972). These studies have shown short-term forgetting over longer retention intervals, but mixed findings as to whether interference is affected by the modality and / or content of a filled intervening task. Moreover, it is likely that tactile information is in constant interaction with visual and spatial information either directly through vision or indirectly via visual imagery. Nevertheless, Gallace and Spence (2014) tentatively conclude that the balance of evidence supports the case that immediate memory for the location of touches is supported by multiple memory systems, including a peripheral modality-specific sensory store for touch and a more central multimodal working memory system.

In Experiment 2, we tested participants' memory for touched facial locations. The experiment aimed to further determine the similarities and differences between verbal, visual and tactile immediate memory, and examined whether the Ward *et al*. (2010) findings observed for words could also be found in the tactile modality. If the Ward *et al*. findings are replicated with touches we would expect participants will tend to initiate IFR of a short series of touches with the first tactile location and continue recall in a forward order. In longer sequences, we would expect recall to be initiated with one of the last four tactile spatial locations, leading to more extended recency effects.

Method

Participants. Twenty-one unpaid volunteer students from the University of Essex participated in this experiment.

Materials and Apparatus. The materials consisted of soft cotton buds to administer the touches and sets of 30 small numbered removable stickers that were positioned in the locations of participants' faces as shown in Figure 6. Participants responded by clicking, using a computer mouse, on the corresponding locations of a visual display of a face presented to the participants via the Supercard application on an Apple Macintosh Computer.

--Figure 6 about here--

Design. The experiment used a within-subject design. There were two within-subjects independent variables: list length with 11 levels (1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 15 touched facial locations) and serial position with up to 15 levels. The dependent variables were equivalent to those used in Experiment 1.

Procedure. Participants were tested individually. Each participant sat next to the experimenter so that both could see the computer monitor. Before testing commenced, the participant closed their eyes and the experimenter stuck a total of 30 small stickers onto the participant's face in the locations illustrated in Figure 6. Unbeknownst to the participant, the stickers were numbered from 1 to 30. The participants were instructed that they would receive a series of between 1 and 15 touches with a cotton bud and that they were asked to try to remember the touched locations which they were to recall in any order that they like.

On each trial, participants were instructed to keep still and keep their eyes closed during the presentation of the stimuli. At the start of the trial, there was a warning tone, and then the experimenter touched between 1 and 15 locations on the participants face. The experimenter wore headphones and heard (out of earshot of the participant) a random set of numbers from 1 to 30 indicating which numbered location on the participants' face to touch. In order to maintain a steady and accurate rate, the presentation rate needed to be set at 1 touch every 1.5 seconds. After the last touch to the face, there was an auditory cue to recall.

Following the auditory cue, participants opened their eyes to see a schematic face displayed on the computer screen with 30 unnumbered circles positioned in the corresponding locations to the 30 stickers on the participants' face. The participant was encouraged to consider the visual face to be a mirror: a touch on the bottom of the right ear would be recalled by clicking the circle on the bottom of the ear that was displayed closest to the right hand side of the screen. The participant clicked on the circles in any order that they liked. The computer circles turned orange upon their selection and could not be selected twice on the same trial. It was also not possible to select more circles at test than had been presented. A pair of boxes on the right hand side of the screen indicated the number of touches that had been presented on that trial and the number of circles that had so far been selected. As in Experiment 1, the participants could only use the "submit" button once they had selected as many circles at test as there had been touches. Pressing the "submit" button initiated the next trial.

Participants performed two practice trials of 7 items, followed by two blocks each of 22 experimental trials. Within each block, there were 2 trials of each of the 11 different list lengths. The order of these trials within each block was randomised. Participants were encouraged to take a short break between the first and second blocks.

Results

Overall accuracy. The open triangles in Figure 1A show the mean proportions of touched locations correctly selected at each of the 11 list lengths. A within-subjects ANOVA with one factor list length (with 11 levels, list lengths 1-8, 10, 12, and 15) revealed that there was a highly significant effect of list length, $F(10, 200)=30.9$, $MSE = .011$, $\eta^2_p = .607$, $p < .001$. Pairwise comparisons of the main effect showed that the proportion of touched locations that were accurately recalled decreased with increasing list length.

Serial position curves. Figure 2B shows the serial position curves for the eleven different list lengths. Appendix A2 shows the results of the statistical analyses performed on the data at each list length. At short to medium list lengths, there were no significant serial position effects. At medium to long list lengths, more specifically 7, 8, 10 and 15, IFR was far less accurate and there were bowed serial position curves, with significant recency effects and significant primacy effects at list lengths 10 and 15.

Probability of First Recall (PFR). Figure 3B shows the mean probability for each list length that the first touched location selected was (a) the first touched location that was presented, (b) one of the last four touched locations that were presented, (c) any of the other touched locations that had been presented, or (d) a touched location that had not been presented.

The probability of initiating recall with the first list item decreased significantly as list length increased, $F(10, 200)=33.2$, $MSE = .046$, $\eta^2_{\mathrm{p}} = .624$, $p < .001$. The probability of initiating recall with one of the last four tactile stimuli increased significantly as list length increased, $F(9, 180)=7.37$, $MSE = .057$, $\eta^2_{\mathrm{p}} = .269$, $p < .001$. The probability of initiating recall with any of the other touched locations increased significantly as list length increased, $F(5, 100)=8.79$, $MSE = .030$, $\eta^2_{\mathrm{p}} = .305$, $p < .001$. There was a non-significant effect of list length on the probability of initiating recall with a non-presented location, $\mathrm{F}(10,200) = 1.50$, $\mathrm{MSE} = .038$, $\eta^2_{\mathrm{p}} =.070$, $p = .141$.

The effect of first recall on the serial position curves. Figure 4D shows the serial position curves for data conditionalized by trials in which recall initiated with serial position 1 (that is, when

P(FR=SP1)) using free recall (FR) scoring. There is little evidence of clear patterns of primacy or recency in this subset of data. Appendix B2 shows the results of the statistical analyses performed on the data at each list length. For every list length, there was a non-significant main effect of serial position.

Figure 4E shows the serial position curves for data conditionalized by trials in which recall initiated with one of the last four serial positions (that is, when P(FR=Last 4)) using free recall (FR) scoring. It is clear that there are more extended recency effects and reduced primacy effects in this subset of data. Appendix C2 shows the results of the statistical analyses performed on the data at each list length. There was a significant main effect of serial position for all list lengths, with the exception of list length 5.

Finally, Figure 4F shows the serial position curves for data conditionalized by trials in which recall initiated with serial position 1 (that is, when P(FR=SP1)) using serial recall (SR) scoring. There is limited evidence for primacy effects but no recency effects in this subset of data. Appendix D2 shows the results of the statistical analyses performed on the data at each list length. There was a significant main effect of serial position only at list length 5.

An analysis of output transitions using Lag-CRP curves. Figure 5B shows the lag-CRP curves for the tactile stimuli. As can be observed, the lag-CRP curves obtained with the non-verbal tactile stimuli in Experiment 2 are similar to those typically obtained from IFR of verbal lists. Figure 5B clearly shows asymmetric lag recency effects at different list lengths, and thus shows forward-ordered recall with tactile stimuli.

Discussion

Experiment 2 showed that participants who performed IFR using touched facial locations showed patterns of data that had certain similarities to those obtained from previous studies using words (e.g., Ward, *et al*., 2010) and sequences of visuo-spatial locations (Experiment 1). To our knowledge, this data set represents the most extensive analysis of the effects of list length on the IFR of tactile stimuli.

Critically, Experiment 2 showed that participants tended to initiate recall with the first item in the list when the list was short, but showed an increasing tendency to initiate recall with one of the last four items as the sequence length increased. Although there was only limited evidence that participants showed "ISR-like" recall with short lists when the same data were examined using SR scoring, there was nevertheless clear evidence of forward recall more generally in the output order (the prevalence of Lag +1 transitions). There was also clear evidence that there was increased recency and reduced primacy when recall initiated with one of the last four serial positions.

These findings provide further evidence that the tendency to initiate recall of short lists with the first list item is not limited to language-specific mechanisms such as a speech input, speech output or verbal short-term memory, but reflect either general multimodal memory mechanisms or similar memory mechanisms operating in different domains (cf. Guérard & Tremblay, 2008; Hurlstone *et al*., 2014). However, the findings suggest that the forward ordered nature of recall of short lists of tactile presentations may be somewhat reduced relative to verbal and non-verbal visuo-spatial lists.

Experiment 3

Experiments 1 and 2 showed that the list length effects in IFR observed by Ward *et al*. (2010) with lists of words were also observed with sequences of visuo-spatial locations (Experiment 1) and to a lesser extent with sequences of touched facial locations (Experiment 2). In Experiment 3, we sought to ensure that these similarities were not the result of participants verbally recoding the (nominally) non-verbal stimuli. We addressed this concern by extending our examination of visuo-spatial locations (Experiment 1) to include a condition in which participants performed the task under AS. AS has been shown to reduce (but not prevent) the tendency to initiate recall with the first list item in lists of words (Grenfell-Essam *et al*., 2013), and this has been taken to indicate that verbal rehearsal contributes (but is not strictly necessary) for the "ISR-like" pattern of recall.

Method

Participants. A total number of 40 students from the University of Essex were recruited as participants for this experiment in exchange for course credit.

Materials. The stimuli were identical to those used in Experiment 1.

Design. The experiment used a mixed factorial design. The between-subjects independent variable was the degree of concurrent articulation with two levels, such that there was a No AS group and an AS group. There were two within-subjects independent variables: list length, with 11 levels (1, 2, 3, 4, 5, 6, 7, 8, 10, 12 and 15 items presented) and serial position with up to 15 levels. The dependent variables were equivalent to those used in Experiments 1 and 2.

Procedure. The procedure was nearly identical to that used in Experiment 1. The only difference was that half of the participants were asked to repeat the word 'the' throughout the presentation of the stimuli, and the session was recorded to ensure that participants complied with these instructions.

Results

Overall accuracy. Figure 1B shows the mean proportion of locations correctly selected at each of the 11 list lengths. A 2 (Group: AS or No AS) x 11 (list length: 1-8, 10, 12, 15) mixed ANOVA revealed that there was a non-significant main effect of group, $F(1, 38)=2.28$, $MSE = .035$, $\eta^2_p = .057$, $p = .139$, a highly significant main effect of list length, $F(10, 380)=244.2$, $MSE = .004$, $\eta^2_p = .864$, $p < .001$, and a significant interaction, $F(10, 380)=1.85$, $MSE = .004$, $\eta^2_p = .047$, $p = .050$. Thus, there was little evidence that recall of the spatial locations was affected by the AS.

Serial position curves. Figure 7 shows the serial position curves for each of the 11 different list lengths in the No AS (Figure 7A) and the AS groups (Figure 7B). As can be seen, recall is close to ceiling levels for list length 1, the curves are relatively flat for list lengths 2-4, and there appear to be more marked effects of serial position at list lengths 5 and greater. In addition, there were very similar serial position curves in both the No AS and AS groups.

--Figure 7 about here--

The serial position curves were analysed at each list length, using a series of 2 (Group: AS group or No AS group) x *n* (serial positions: 1 to *n*) mixed ANOVAs (where *n*, here and henceforth, refers to the list length). The exact statistics for the main effects and interaction for each list length can be found in Appendix A3. In summary, AS had a non-significant effect for all but one list length (list length 8, where recall was greater in the No AS group relative to the AS group). The main effect of serial position was significant for list lengths 5-15. Specifically, analyses of the effect of serial position at list length 5 showed primacy, the effects at list lengths 6 to 15 showed both primacy and recency; however list length 15 showed extended recency effects. Finally, all of the interactions between serial position and AS were non-significant, except for list length 15.

Probability of First Recall (PFR). Figure 8A and Figure 8B show data from the No AS and AS conditions of Experiment 3. Each panel plots the mean probability for each list length that the first rectangle selected was (a) the first rectangle that was presented, (b) one of the last four rectangles that were presented. For completeness, the Figure also shows the mean probability for each list length that the first rectangle selected was any of the other rectangles that had been presented, or a rectangle that had not been presented.

--Figure 8 about here--

We consider first the probability of initiating recall with the first list item. The data for both the No AS and the AS Groups and were analysed by a 2 (Group: No AS and AS) x 11 (List length 1-8, 10, 12 and 15) mixed ANOVA. There was a non-significant main effect of group, $F(1, 38)=.150$, $MSE = .365$, $\eta^2_p = .004$, $p = .700$, a highly significant main effect of list length, $F(10, 380)=92.4$, $MSE = .026$, $\eta^2_p = .709$, $p < .001$, and a non-significant interaction, $F(10, 380)=.404$, *MSE* = .026, η^2_p = .011, *p* = .945. Thus, initiating recall with the first list item was affected by the list length, but there was little evidence that it was affected by AS.

A complimentary 2 (Group: No AS and AS) x 10 (List lengths 2-8, 10, 12 and 15) mixed ANOVA was conducted on the probability of initiating recall with one of the last four list items. There was a non-significant main effect of group, $F(1, 38)=0.046$, *MSE* = .464, η^2_p = .001, *p* = .831, a highly significant main effect of list length, $F(9, 342)=8.49$, *MSE* = .028, η^2_p = .183, $p < .001$, and a non-significant interaction, $F(9, 342)=.834$, *MSE* = .028, η^2_p = .021, *p* =.585 . Again, initiating recall with one of the last four list items was affected by the list length, but there was little evidence that it was affected by AS.

The effect of first recall on the serial position curves. Figure 9A and Figure 9B shows the serial position curves for the No AS and AS conditions of Experiment 3 for those trials in which recall initiated with serial position 1 (that is, when P(FR=SP1)) using free recall (FR) scoring. It is clear that there are more extended primacy effects and reduced recency effects in this subset of data. For each list length, these serial position curves were analysed by a 2 (group: AS or No AS) x *n*-1 (serial positions: 2 to *n*) mixed ANOVA using FR scoring. The exact statistics for the main effects and interaction for each list length can be found in Appendix B3. In summary, the main effect of serial position was significant for list lengths 6, 8, 10 and 15. At all list lengths, the main effects of AS were non-significant and there were no significant interactions between group and list length.

--Figure 9 about here--

Figure 9C and Figure 9D show the serial position curves for the No AS and AS conditions of Experiment 3 for those trials in which recall initiated with one of the last four presented rectangles. These SPCs were analysed by a 2 (group: AS or No AS) x *n* serial position mixed ANOVA. The exact statistics for the main effects and interaction for each list length can be found in Appendix C3. In summary, there was a significant main effect of serial position for all sequences with 3 squares or more, with the exception of list length 4, reflecting extended recency effects and somewhat reduced primacy effects. There were relatively few significant effects marking AS but there was a significant main effect of AS for list length 8 while all interactions were non-significant.

Figure 9E and 9F shows the serial position curves for the No AS and AS conditions of Experiment 3 for those trials in which recall initiated with serial position 1 using serial recall (SR) scoring. It is clear that participants tended to output the first few rectangles in a forward serial order, despite the fact that this is not required of them. For each list length, these serial position curves were analysed by a 2 (group: AS or No AS) x n-1 (serial positions: 2 to n) mixed ANOVA using SR scoring. The exact statistics for the main effects and interaction for each list length can be found in Appendix D3. In summary, the main effects of serial positions were significant for list lengths, with the exception of list length 4. At all list lengths, there were non-significant main effects of AS and non-significant interactions between list length and group.

An analysis of output transitions using Lag-CRP curves. Figure 5C shows the lag-CRP curves for the visuo-spatial stimuli in the No AS conditions, Figure 5D shows the lag-CRP curves for the visuo-spatial stimuli in the AS conditions. As can be observed, the lag-CRP curves obtained with the non-verbal visuo-spatial stimuli in Experiment 3 are similar to those typically obtained from IFR of verbal lists., and there is little or no effect of AS. Figures 5C and 5D clearly show asymmetric lag recency effects at different list lengths in both conditions, and thus show forward-ordered recall with visuo-spatial stimuli that was not mediated by verbal recoding.

Discussion

Experiment 3 further confirmed that the Ward *et al*. (2010) findings obtained with lists of words can be generalized to situations in which non-verbal visuo-spatial locations are used as stimuli. Regardless of AS, participants' accuracy decreased as the list length increased and there were bowed serial position curves at longer list lengths. Additionally, there was a decreasing tendency to initiate recall with the first stimulus with increasing list length, an increasing tendency to initiate recall with one of the last four stimuli with increasing list length, and the serial position curves had very different patterns for trials in which recall started with the first or one of the last four list items.

Critically, participants tended to initiate IFR of a short list of words in an “ISR-like” manner. The demonstration of similar findings under AS further confirms that the findings presented here are not due to participants verbally recoding the locations. The data provide convincing evidence that the Ward *et al*. (2010) findings do not necessitate a language-specific mechanism, such as the direct output of an ordered verbal short term memory that was increasingly likely to be overwritten with increasing list items.

Despite the similarities between the data presented here and those of Ward *et al*. (2010), it should be noted that there are some differences in the shapes of the PFR curves. The tendency to initiate recall with the first stimulus item is relatively well maintained with increasing list lengths with words: 1.00, .98, .97, .89 for list lengths 1-4 (Ward *et al*., 2010, Experiment 3), but for visuo-spatial stimuli, the corresponding values were .93, .72, .58, .52 in the No AS group and .99, .68, .60 and .49 in the AS group. In fact, the data for visuo-spatial stimuli are more similar to those of verbal stimuli under AS (Spurgeon *et al*., 2014), and may suggest that IFR of words may additionally be underpinned by a forward-ordered rehearsal mechanism. This comparison and possibility was addressed more fully in Experiment 4.

Experiment 4

The aim of Experiment 4 was to compare more directly the IFR performance on lists of between 1 to 15 words with the IFR performance on lists of 1 to 15 non-verbal stimuli. The findings from Experiment 3 had suggested that the tendency to initiate recall with the first list item was stronger with words compared with non-verbal stimuli. However, before drawing this conclusion, it is necessary (1) to contrast the two stimulus domains directly in a single experiment, and (2) to ensure that the presentation and testing of the non-verbal stimuli share as similar a methodology as possible to the presentation and testing of the verbal stimuli.

We identified two main differences between the IFR of lists of words used by Ward *et al*. (2010) and the IFR of visuo-spatial rounded rectangles used in Experiment 3. First, the IFR of lists of words occurred in the absence of any external cues, but the IFR of lists of visuo-spatial stimuli occurred in the presence of a set of 30 visuo-spatial rounded rectangles that remained on the screen at test in Experiment 3. Thus, any differences observed between the IFR of words and visuo-spatial stimuli may reflect either differences in the stimulus domain or differences between the degree of environmental support that was available at test: the test of verbal stimuli was recall whereas the test of non-verbal stimuli was recognition. Second, participants undertaking the IFR of lists of words typically output far fewer responses than items in the list (at least for longer list lengths). By contrast, participants in the visuo-spatial task were made to select as many stimuli at test as the number of stimuli presented. A highly likely consequence is that some of the responses in the visuo-spatial stimuli were forced guesses, particularly at longer list lengths.

In order to control for these two differences, Experiment 4 contrasted the IFR of lists of between 1 and 15 words with the IFR of lists of between 1 and 15 visuo-spatial circles. The circles appeared one at a time in different locations of the screen, and at test, participants saw a blank screen and had to click at the locations of the circles in whatever order they liked. They were encouraged not to guess and they were allowed to make as many or as few responses as they wished (but no more responses than there had been stimuli).

Thus, in Experiment 4 there were two groups of participants (Verbal and Non-Verbal Stimuli), and in each group participants performed one block of IFR trials with AS and another without AS. Specifically, in each block, participants received five trials for each of eleven list lengths (lists of 1-8, 10, 12 and 15). Now with more carefully matched methodologies, the extent of the ISR-like tendencies in IFR of short lists of verbal and non-vernal stimuli could be more closely compared.

Method

Participants. A total number of 40 students from the University of Essex participated in exchange for course credit in this experiment.

Materials. Stimuli were presented using the 'Supercard' application via an Apple Mac Computer. On each trial, half of the participants saw a list of up to 15 words that were randomly selected for each participant from a subset of 412 words from the Toronto Word Pool (Friendly, Franklin, Hoffman, & Rubin, 1982). Each word was individually presented in 52-pt Times New Roman font in the centre of the screen. The other half of the participants saw a sequence of black circles, where each circle had a diameter of 35mm and its spatial location was selected at random from 412 different spatial locations on the screen, in a 285mm x 165mm frame with a grey background. Responses were recorded using the computer mouse of the Apple Mac Computer for the visuo-spatial stimuli and on paper for the verbal stimuli.

Design. The experiment used a mixed factorial design. The between-subjects independent variable was the stimulus domain with 2 levels: verbal and visuo-spatial stimuli, such that there was a verbal stimuli group and a visuo-spatial stimuli group. There were three within-subjects independent variables: the degree of concurrent articulation with 2 levels (No AS and AS), list length, with 11 levels (1, 2, 3, 4, 5, 6, 7, 8, 10, 12 and 15 items presented), and serial position with up to 15 levels. The dependent variables were equivalent to those used in Experiments 1-3.

Procedure. Participants were tested individually, and they were informed that they would be shown two practice lists of seven stimuli (one list with and one list without AS), followed by 110 experimental lists of stimuli. The experimental trials were arranged into two blocks; each block contained 55 trials (five trials of each of the eleven different list lengths). The stimuli appeared on the screen for 0.75s, and the screen was blank during the 0.25s inter-stimulus interval. The order of the blocks was counterbalanced across participants, and within all blocks the order of the list lengths was randomized. Each trial started with a pre-cue instruction either to remain quiet (No AS) or to repeat "1, 2, 3, 4" (AS) warning tone. Following a computer mouse click, participants saw a sequence of between 1 and 15 stimuli presented one at a time. The words appeared in the center of the screen; the visuo-spatial circles appeared at different screen locations. For the No AS condition, participants saw the stimuli in silence as they were presented. For the AS condition, participants saw the stimuli whilst repeating the sequence “1, 2, 3, 4” during the presentation of the list. During the presentation of both types of stimuli, the location of the curser was locked to a location at the right hand edge of the screen. At the end of the list there was an auditory cue for recall. The participants in the Verbal group wrote down as many words as they could remember, in any order that they wished in a lined response grid. The participants in the Non-Verbal group clicked at the locations of the screen where they thought that they had seen the circles, and they were free to respond in any order that they wished. After the participant was satisfied that they had completed their recall, they pressed the “submit” button which started the next trial.

Results

Overall accuracy. Figure 1C shows the overall proportion of circles that were correctly recalled and Figure 1D shows the overall proportion of words that were correctly recalled. In each panel, overall accuracy is plotted by list length for both the No AS and AS conditions. In all conditions, the proportion of correct responses decreased with increasing list length. It is clear that the accuracy in recalling the locations of the circles (Figure 1C) was considerably lower than the accuracy in recalling the words (Figure 1D). In addition, whilst there was little or no difference between the accuracy of the No AS and AS trials in the visuo-spatial stimuli group (Figure 1C), there was a marked difference between the accuracy of the No AS and AS trials in the verbal condition (Figure 1D).

Table 1A summarizes a 2 (Stimuli: Verbal or Visuo-spatial) x 2 (Trial type: AS or No AS) x 11 (list length: 1-8, 10, 12, 15) mixed Analysis of Variance (ANOVA) that was performed on the proportion of correct recalled items. Overall, there was a significant main effect of list length, suppression and stimuli. There was also a significant interaction between list length and stimuli group and between suppression and stimuli group, a significant interaction between list length and suppression, as well as a significant three-way interaction between list length, suppression, and stimuli.

In order to further explore the three-way interaction, a 2 (Trial type: AS or No AS) x 11 (list length: 1-8, 10, 12, 15) ANOVA was performed on each of the verbal and visuo-spatial stimuli groups (see Table 1B). In the verbal stimuli group there was a highly significant list length effect, as well as a significant effect of AS and a list length by AS interaction. By contrast, in the visuo-spatial group, there was a highly significant main effect of list length, but a non-significant effect of AS and a non-significant interaction.

--Table 1A & 1B about here--

Serial position curves. Figure 7C-7F shows the serial position curves for each of the 11 different list lengths in both the No AS and AS conditions for the Verbal and Visuo-spatial stimuli groups. The serial position curves for each stimulus type were analysed at each list length, using a series of 2 (suppression: AS or No AS) x n (serial positions: 1 to n) mixed ANOVAs. The exact statistics for the main effects and interaction for each list length can be found in Appendix A4.

In summary, for the visuo-spatial group, AS had a non-significant effect for all but one list length (LL 10). The main effect of serial position was significant for list lengths 6-15. More specifically, the curves at list lengths 2 and 3 were linear; list lengths 4-8 showed both primacy and recency, while list lengths 10 and greater had extended recency effects. Finally, all of the interactions between AS and serial position were non-significant.

For the verbal group, the main effect of serial position was significant for list lengths 3-15. More specifically, list lengths 3-5 showed primacy, list lengths 6-8 showed both primacy and recency, whereas the effects at list lengths 10-15 showed extended recency effects. There was a significant reduction due to AS at all list lengths, and also a significant interaction between list length and AS for list lengths 3-15. AS greatly affected earlier serial positions, but led to a 1-item recency advantage.

The probability of first recall (PFR) data. Figure 8C-8F shows the proportion of trials in which items from different serial positions were recalled first, for each of the 11 different list lengths and for both No AS and AS for the verbal and visuo-spatial stimuli groups respectively. Figures 8C and 8D refer to the IFR data from the visuo-spatial circles task, with and without AS, respectively; and Figures 8E and 8F refer to the IFR data from the lists of words, with and without AS. For the lists of visuo-spatial stimuli (Figures 8C and 8D), participants tended to initiate recall with the first circle on short lists but initiated recall with one of the last four circles with longer lists. There was a high degree of error in accuracy, especially when compared to the verbal stimuli, but little effect of AS on where recall started. For the lists of words (Figures 8E and 8F), participants also tended to initiate recall with the first word on short lists but initiated recall with one of the last four words with longer lists. There were very few initial errors, but there was a large effect of AS on where recall started: the tendency to initiate recall with the first word was reduced (but not eliminated) when lists of words were recalled under AS.

Table 1A shows the results of two 2 (Stimuli: Verbal or Visuo-spatial) x 2 (Trial type: AS or No AS) x 11 (List length: 1-8, 10, 12, 15) mixed ANOVAs that were calculated on the proportion of trials where participants initiated their recall with ‘Serial Position 1’ and the ‘Last 4’ items respectively. Both ANOVAs showed significant main effects of list length, suppression and stimuli group as well as significant interactions between list length and stimuli group and between suppression and list length. Furthermore, there was a significant interaction between suppression and stimuli group, as well as a significant three-way interaction between AS, list length and stimuli group.

Figure 8 shows that despite the differences in accuracy levels in the verbal and visuo-spatial tasks, both figures show that as the list length increased, the tendency to initiate recall with the first item decreased, and the tendency to start with the last four items increased. Finally, it is also noteworthy that AS, unlike in the verbal group, did not have an adverse effect on the tendency to initiate IFR with the first list item, implying that recall in visuo-spatial tasks was not aided through language. Overall, the PFR data for both domains show that this list length tendency is present for both verbal and visuo-spatial stimuli, implying similar mechanisms of recall in both modalities.

The effect of the first recall on the serial position curves. Figures 10A and 10B show the effect of list length and AS on the proportion of items recalled, for trials where recall was initiated with Serial Position 1 for the visuo-spatial groups. For each list length, these serial position curves were analysed by a 2 (Trial type: AS or No AS) x n -1 (serial positions: 2 to n) mixed ANOVA using FR scoring. The exact statistics for the main effects and interactions for each list length can be found in Appendix B4. For the visuo-spatial group, the main effect of serial position was significant for list lengths 5 and 7. There was no significant main effects of AS, and all interactions between list length and suppression were non-significant except for list length 3.

--Figure 10 about here--

Figures 11A and 11B show the effect of list length and AS on the proportion of items recalled, for trials where recall was initiated with Serial Position 1 for the corresponding verbal group. The exact statistics for the main effects and interactions for each list length can also be found in Appendix B4. For the verbal stimuli group, the main effect of AS was significant for list lengths 3-8, which showed that AS reduced recall of lists of words relative to the No AS conditions. The interaction between AS and serial position reached significance for list lengths 4, 8 and 15, showing that AS tended to reduce early and middle serial positions but enhance a single-item recency. Finally, there was a significant main effect of serial position for list lengths 5, 10, and 15, showing significant primacy effects and (at longer list lengths) significant recency effects.

--Figure 11 about here--

Figures 10C and 10D and Figures 11C and 11D show the effects of AS and list length on the proportion of circles (Figures 10C and 10D, for No AS and AS visuo-spatial conditions, respectively) and words (Figures 11C and 11D, for No AS and AS verbal conditions, respectively) recalled in any order for trials in which recall was initiated with one of the last four presented items. These SPCs were analysed by a 2 (Trial type: AS or No AS) x *n* serial position mixed ANOVAs, one per each stimuli group. The exact statistics for the main effects and interactions for each list length can be found in Appendix C4.

For the visuo-spatial group, there was a significant main effect of serial position for all list lengths, reflecting extended recency effects. There were significant main effect of AS only for list lengths 4, 7 and 15 reflecting reductions in recall under AS at these three list lengths, but all the interactions between AS and serial position were non-significant. For the verbal stimuli group, there was a significant main effect of serial position for all list lengths of 5 words or more, reflecting extended recency effects. Additionally, there was a significant main effect of AS for list lengths 5 and greater; and significant interactions between AS and serial position at list lengths 4-7, 12, and 15. AS reduced verbal recall, particularly at early serial positions.

Figures 10E and 10F and Figures 11E and 11F show the SPCs for the same data coded using SR scoring for the No AS and AS list length groups for both the verbal and visuo-spatial group. For each list length within each stimuli group, these serial position curves were analysed by a 2 (Trial type: AS or No AS) x *n* -1 (serial positions: 2 to *n*) mixed ANOVA using SR scoring. The exact statistics for the main effects and interaction for each list length can be found in Appendix D4.

For the visuo-spatial group, the main effect of serial position was significant for list length 5, indicating some evidence of forward ordered recall. There was only limited effects of AS. There was a non-significant effect of AS for all list lengths, and there was only one significant interaction between AS and serial position at list length 3. By contrast, for the verbal stimuli group, the main effect of serial position was significant for all list lengths, indicating strong serial ordered recall. There was a significant main effect of AS for all list lengths except list length 7, as well as a significant interaction for all but list lengths 5 and 7. These data show that the IFR of the lists of words was performed in an ISR-like manner and that it was more affected by AS.

An analysis of output transitions using Lag-CRP curves. Figures 5E and 5F show the lag-CRP curves for the visuo-spatial stimuli in the No AS and AS conditions, respectively; and Figures 5G and 5H show the lag-CRP curves for the verbal stimuli in the No AS and AS conditions, respectively. As can be observed, the lag-CRP curves obtained with the non-verbal visuo-spatial stimuli in Experiment 4 are similar to those typically obtained from IFR of verbal lists, such as those shown in Figures 5G and 5H. Whilst there appears to be some effect of AS on the verbal stimuli there is no such effect with the visuo-spatial stimuli. All four plots show clear asymmetric lag recency effects at different list lengths, and thus show forward-ordered recall in IFR with visuo-spatial and verbal stimuli.

Discussion

The aim of Experiment 4 was to equate the methodologies of verbal and visuo-spatial IFR tasks, to enable further comparison between the two stimulus domains. Although lists of words and lists of visuo-spatial circles are inherently different, further efforts were made to ensure that the methodologies used in both modalities were as similar as possible.

There were five general findings from Experiment 4. First, the overall performance in the visuo-spatial task of the present experiment was much lower than in the previous experiments as well as lower than performance in the verbal task. This is likely to be because participants had to click on the exact spatial locations of a sequence of visuo-spatial stimuli in Experiment 4, in the absence of any environmental support for those locations. Furthermore, it is also possible that visuo-spatial recall in Experiments 1 and 3 benefitted from additional guesses. Undeniably, guesses could still occur in the present experiment, however these were not supported by the presentation of possible items, since participants saw a blank screen at test.

Secondly, and consistent with the previous experiments, AS did not have a marked effect on the performance in the visuo-spatial task, implying that the results obtained in the visuo-spatial task were on the whole unaided by the participants' use of verbalization (and verbal rehearsal). In contrast, although verbal memory performance was greatly reduced by AS, the task remained possible, a result suggesting that verbal rehearsal augmented (but was not strictly necessary) for IFR (a result similar to Grenfell-Essam *et al*., 2013; and Spurgeon *et al*., 2014).

Thirdly, the shapes of the serial position curves in the visuo-spatial task looked similar to those of the verbal task performed in silence. When performed under AS, verbal serial position curves showed increased recency effects especially in the longer list lengths. This shows that despite the different levels of performance in both tasks, primacy and recency effects can be seen in non-verbal stimuli, resulting in bowed serial position curves.

Additionally, the PFR data showed that a similar strategy was used to recall in both stimulus domains, despite the different levels of performance observed in the verbal and visuo-spatial IFR. In the verbal task, the tendency to initiate recall with the first list item was the modal response for all short list lengths until between list length 7 and 8 in the No AS trials, and between list length 4 and 5 under AS. In the visuo-spatial group, the tendency to initiate recall with the first list item was the modal non-error response for the No AS trials until between list length 5 and 6, whilst in the AS trials, the tendency to initiate recall with the first list item was the modal non-error response from list length 5 to 6. This reinforces the idea that regardless of the stimulus type, participants tended to start with the stimulus in the first serial position in short lists, and initiated recall with one of the last 4 presented items in longer lists.

However, the tendency to initiate recall with the first item remained high over list lengths 1-4 with verbal stimuli (.99, .97, .92, .87) but decreased more sharply with visuo-spatial circles (0.80, 0.66, 0.54, 0.42). One possibility is that these differences reflect differences in overall accuracy between the two types of stimuli: verbal stimuli might vary in more dimensions (orthographic, phonological, semantic, temporal) than visuo-spatial (spatial, temporal) and that to initiate recall of the first item necessarily requires that that first item is accessible. A second possibility is that the the effect of temporal order on the IFR of visuo-spatial stimuli is diluted by the effects of the spatial proximity of the items and the position of the items relative to the cursor at the start of test. A third possibility is that a general forward-ordered tendency could be augmented for verbal stimuli by co-articulating and / or rehearsing short sequences of 3-4 items which are later retrieved in forward-order. In line with this third possibility, the tendency to initiate recall with the first item declined markedly over list lengths 1-4 with verbal stimuli when presented under AS.

Finally, a comparison of the serial position curves scored with FR and SR scoring revealed that two of the largest factors contributing to the shapes of the curves were the list length and the scoring system that was used. The resultant serial position curves showed that the first item recalled was a clear indicator of which other list items were likely to be recalled. When recall was initiated with the first presented item, there was increased primacy and reduced recency effects, but when recall was initiated with one of the last 4 items, there was decreased primacy and extended recency effects. Resultant serial position curves using SR scoring revealed a tendency to recall items in forward order in both modalities, albeit that this tendency was stronger in the performance of the verbal group in the No AS trials.

In summary, we found further evidence that the novel finding by Ward *et al*. (2010) is not confined to verbal material, but can be extended to other modalities, a finding supporting the claim that this list length strategy is not exclusively underpinned by language-specific codes. The Experiment also provides compelling evidence that there are similarities in the effects of list length on the serial position curves and output orders in the IFR of verbal and non-verbal stimuli, supporting claims of functional similarities between verbal ad non-verbal stimulus domains.

General Discussion

The current set of experiments had two major aims. The first aim of this research addressed the question of why participants show a strong tendency to initiate IFR of a short list of words with the first list item (Corballis, 1967; Neath & Crowder, 1996; Ward, *et al*. 2010). Specifically, we examined whether this tendency was language-specific, perhaps reliant on verbal input or output buffers, or required a forward-ordered verbal short-term memory. To this end, we examined whether a similar tendency could be observed with non-verbal stimuli, and asked participants to perform IFR on short and long lists of visuo-spatial rounded rectangles and touched facial locations. The second aim of the research was to examine functional similarities and differences between verbal and non-verbal IFR. In so doing, we provided a rich data set examining the IFR of non-verbal stimuli, systematically examining the serial position curves and the output orders over a wide range of list lengths. We additionally compared verbal IFR directly with non-verbal visuo-spatial circles over identical range of list lengths.

On the tendency to initiate IFR of a short list of words with the first list item

Ward *et al*. (2010) systematically manipulated list length and showed that participants who were presented with a short list of words for IFR, typically recalled in an "ISR-like" manner. The findings from the current four experiments not only replicated that finding (verbal lists, Experiment 4), but also extended and generalized the finding to the IFR of short lists of non-verbal stimuli such as visuo-spatial locations (Experiments 1, 3, and 4) and touched facial locations (Experiment 2). In the IFR of all types of stimuli, participants tended to initiate recall of short lists with the first list item and tended to initiate recall of longer lists with one of the last four presented items. For visuo-spatial stimuli as well as for verbal stimuli, the initial recall also predicted the other items recalled on that trial: when recall began with the first list item, participants subsequently recalled other early list items, with greater primacy and reduced recency, whereas when recall began with one of the last list items, participants subsequently recalled other late list items, with greater primacy and reduced recency effects.

One major implication of these findings, therefore, is that the Ward *et al*. (2010) finding need not be exclusively underpinned by a language-specific mechanism. This conclusion was further supported by the additional finding that IFR of visuo-spatial stimuli was essentially unaffected by concurrent AS. When one additionally considers that these list length effects are also found in the absence of phonological coding (Spurgeon *et al*., 2014) and are also observed under continual distractor free recall conditions (Spurgeon *et al*., in press), then the current findings imply that the tendency to initiate IFR of a short list with the first list item is not always mediated by verbal short-term memory or indeed to order-sensitive, language-specific mechanisms. Instead, the finding that participants initiate IFR of short sequences of events with the first list item may reflect a more general property of memory that holds across a range of materials and timescales.

It is possible to speculate on why memory might show this general forward-ordered tendency, even on tasks that do not explicitly require ordered output. One line of argument is that we are often faced with the task of retaining information in serial order, such as learning the sequences of phonemes that allow vocabulary acquisition or learning sequences of motor actions and social behaviors that allow imitation and organized behavior (Lashley, 1951). The ability to plan, represent, and recall novel sequences of both verbal and non-verbal items may therefore be central for higher-level cognitive activities and so may be “hard-wired” into memory processes (e.g., Hurlstone *et al*., 2014). A growing body of evidence suggests that we may naturally parse our continuous experience into separate clusters of temporally-extended events (e.g., Swallow, Zacks, & Abrams, 2009), and a similar clustering of events has been argued to occur in the encoding of groups of words in short-term memory tasks (e.g., Farrell, 2012). Given that serial order information has to be encoded in relation to some start point, the beginning of the list provides a salient boundary from which to develop serially-ordered representations of items. This approach assumes that participants performing IFR of short lists of words recruit those very same memory mechanisms that underpin performance on immediate serial recall (ISR) tasks, where the necessity to retrieve the list in forward serial recall is explicitly requested (e.g., Brown, Neath, & Chater, 2007; Farrell, 2012; Hurlstone *et al*., 2014; Ward, *et al*., 2010).

A second speculative line of argument is that the forward recall of a sequence of events may be a strategy employed by participants whenever they try to recall as many list items as possible from a small set of discrete items. It is often assumed that recall of one or more list items can have both facilitatory and interfering effects on the retrieval of other list items (e.g., Nairne, Ceo, & Reysen, 2007). The successful retrieval of some list items may aid the retrieval of other semantically-related or temporally-neighboring items, leading to semantic clustering and temporal contiguity effects (e.g., Polyn, Norman & Kahana, 2009), but the retrieval of one item may also decrease the accessibility of others through output interference (e.g., Beaman, 2002; Cowan, Saults, Elliott & Moreno, 2002; Oberauer, 2003; Tan & Ward, 2007). Using a cued recall task, Nairne *et al*. found that recalling a target item on a short list of words was facilitated by first having to recall the immediately preceding item (cf., Kahana & Caplan, 2002), whereas retrieving a target item was impaired when participants first had to recall the word that had been presented two words after the target word. Together, these findings suggest that a forward order recall strategy might be effective in maximizing recall of short lists. Indeed, Lohnas and Kahana (2014) have argued that retrieving the immediately preceding two successive items immediately prior to recall results in an even greater advantage to the recall of the third item, a phenomena that they refer to as compound cuing in free recall. There is also additional evidence that in list learning experiments, the recall of all the list items from a large list of words is faster under serial learning than under free recall learning (e.g., Klein, Addis, & Kahana, 2005; Waugh, 1961), albeit that for long lists the initial recall following the first presentation is better under free recall rather than serial recall instructions. To benefit most from these forward-ordered contiguity effects, participants may therefore elect to start at the start of the list whenever possible (and so one must also assume that the ease of access to the first list item may decrease with increasing list length). Proactive interference may contribute to the difficulty in accessing the start of the list for moderate to long lists. Unsworth, Brewer, and Spillers (2011) presented participants with 10-word lists for IFR and showed that there was initially "ISR-like" recall, even with moderate to long list lists on the first few trials. However, as the experiment progressed, so participants shifted from initiating recall at the start of the list to initiating recall with one of the last few list items, with a concomitant decrease in primacy and increase in recency on later trials (see also Dallett, 1963; Goodwin, 1976).

On the functional similarities between verbal and non-verbal memory

Our current experiments provide a rich data set for comparing IFR performance on verbal and non-verbal stimuli, and it is far more extensive than those already published (e.g., Bonnani, *et al*., 2007; Gmeindl *et al*., 2011). We found many similarities in the patterns of data obtained with words (Experiment 4), touched facial locations (Experiment 2) and visuo-spatial rectangles (Experiment 1 and Experiment 3) and visuo-spatial circles (Experiment 4). First, overall accuracy in IFR decreased with increasing list length for all types of stimuli. Second, the serial position curves for very short lists were relatively flat, but as the list length increased, so the curves became increasingly bowed, with increased primacy and recency effects. Third, there were similarities in the PFR data. For all stimuli, participants tended to initiate recall with the first stimulus item on very short lists, but this decreased with increasing list lengths, such that, for all types of stimuli, the modal non-error initial response was one of the last four stimulus items at longer list lengths. Fourth, the resultant serial position curves were greatly affected by the initial recall. For verbal and visuo-spatial sequences, when recall commenced with the first list item, there was greater recency and reduced primacy relative to when recall commenced with one of the last four list items. Finally, for all stimuli, there were clear asymmetric lag recency effects: the transitions between successive outputs at recall were most likely to be between temporal near-neighbors in the list, and there was a tendency to recall in a forward order. The gross similarities between verbal and visuo-spatial stimuli in IFR support the claim by Ward *et al*. (2005) that there may be many similarities in findings across modalities when the methodologies are closely equated.

The similarities observed between verbal and visuo-spatial stimuli in IFR are analogous to the similarities observed between verbal and visuo-spatial stimuli in ISR-related tasks reported by Guérard and Tremblay (2008), who proposed three possible explanations. First, there are separate verbal and visuo-spatial memory stores that each maintain the serial order of items in equivalent ways (e.g., the visuo-spatial sketch pad operates in a comparable manner to the phonological loop, Logie, 1995). Second, there is a non-modular memory that retains the serial order of all stimuli, but the patterns of selective interference arise because different combinations of primary and secondary tasks rely on more or less similar perceptual organization of the stimuli and more or less similar gestural execution of the responses (Jones, Hughes & Macken, 2006; Jones, Macken & Nicholls, 2004). Finally, there is a non-modular memory that retains the serial order of all stimuli, but the patterns of selective interference arise because of the differences in similarity between features of the items in the primary and secondary tasks (e.g., Cowan, 2005; Nairne, 1990; Neath, 1999; Oberauer & Kliegl, 2006). It would appear that these same explanations could equally be applied to the similar patterns of data observed here with IFR.

The most recent work by the first author (Cortis, Dent, & Ward, in preparation) has attempted to isolate which of these three possibilities might best apply to the IFR data. Three groups of participants performed IFR and were presented with (a) lists of between 1 and 16 auditory-verbal words, (b) lists of between 1 and 16 visuo-spatial circles, or (c) simultaneously presented with lists of between 1 and 16 items of both types of stimuli. The participants recalled the auditory-verbal stimuli by saying the words out loud and recalled the visuo-spatial stimuli by clicking on the locations of the circles using the computer mouse. Contrary to a limited-capacity multi-modal short-term memory, the total number of words recalled in the simultaneous words and circles condition was equivalent to the total number of words recalled in the words alone condition. In addition, there was only the smallest dual-task decrement in the recall of the circles. Moreover, the order of recall of the two types of stimuli appeared to be constrained. Participants tended to initiate recall of the short lists of stimuli with the first list item, and tended to initiate recall of longer lists of stimuli with one of the last items; but there also a clear tendency to initiate recall with a word rather than a circle, and then to alternate words followed by circles, and each recalled word was often followed at output by the circle with which it had been simultaneously presented.

Our data appear to at least partially support the theoretical position adopted by Hurlstone *et al*. (2014) who argued that the serial recall of verbal, visual, and spatial memory could be underpinned by multiple, similar, modality-specific computational memory mechanisms. According to Hurlstone *et al*., serial order may be represented by a primacy gradient and positional marking, and serial recall may be achieved by a competitive queuing (CQ) mechanism in which candidate items are considered for output in parallel with the most activated item selected and subsequently suppressed, and finally serial recall is affected by output interference and item similarity. Hurlstone *et al*. noted the similarities between ISR and IFR of short lists, and they also argued that there is only incomplete evidence for analogous mechanisms supporting serial recall of visual and spatial memory, primarily because the relevant studies have not as yet been performed. The current experiments go some way to provide data sets in support of their integrated position, and the as yet unpublished data suggest that there may well be separate capacity limits for auditory-verbal and visuo-spatial stimuli. However, these most recent data collected by the first author also suggest that the retrieval mechanisms of the separate short-term memory stores appear to be not entirely independent, since the recall order appears to be constrained both within- and across-modalities, findings that constrain how serial order should be represented within the nonverbal immediate memory systems.

On the functional differences between verbal and non-verbal memory

The preceding section concentrated on the similarities between verbal and visuo-spatial IFR, but there are also some important differences between the IFR of the different stimulus domains. First, when the tasks were properly equated (Experiment 4), there was a marked difference between the overall accuracy in IFR between the verbal and visuo-spatial tasks. Performance was close to ceiling levels at the shorter list lengths in the verbal task, but was below ceiling in the visuo-spatial data. Second, the primacy and the recency effects with the visuo-spatial stimuli are weaker than those with the verbal stimuli. One possible explanation for this phenomenon is that the temporal order of visuo-spatial stimuli is less important either because the visuo-spatial items are less well bound to the temporal context than for verbal stimuli (Gmeindl *et al*., 2011) or because the output order of responses to visuo-spatial items is additionally affected by the spatial proximity of successive responses which might disrupt the importance in temporal ordering (Gmeindl *et al*., 2011). Alternatively, the individual representations of verbal stimuli may vary more greatly over more stimulus dimensions (e.g., orthographic, semantic) than the visuo-spatial stimuli, and the verbal stimuli may particularly benefit from phonological recoding and rehearsal, which may exaggerate serial position effects.

A third major difference between verbal and visuo-spatial IFR is that verbal IFR but not visuo-spatial IFR was adversely affected by AS. For word lists, the AS reduced overall accuracy, reduced the tendency to initiate IFR of verbal stimuli with the first list item, and resulted in steeper primacy and recency effects. These findings suggest that visuo-spatial IFR is not mediated by verbal recoding, whereas the IFR of verbal words benefits from the phonological recoding that can occur in the absence of AS. These findings could be interpreted as evidence that a Phonological Loop (e.g., Baddeley, 1986, 2000, 2007, 2012) contributes to the forward-ordered tendency in IFR. Although a possibility, such an interpretation would also necessitate that a non-phonological immediate memory mechanism (presumably the Episodic Buffer) must account for the very similar (albeit reduced) patterns of recall in the verbal AS conditions, since words presented visually under AS are assumed not to enter the phonological loop (for related discussion, see Spurgeon *et al*, 2014). An alternative interpretation is that in the absence of AS, the mental representations of the visual words benefit from the additional features associated with phonological recoding, such that at test, individual stimulus items are more discriminable. A third interpretation is that verbal recoding is a necessary requirement to generate streams of ordered visual items (e.g., Jones, 1993) or a fourth interpretation (that represents a modification of the account by Farrell, 2012) is that the effective group size of words within temporal clusters is reduced when the contents of a group cannot be co-articulated.

Finally, we did not perform a non-verbal secondary task such as manual tapping. If there exists separate visuo-spatial and verbal short-term stores and if each has its own modality-specific rehearsal process, then one might imagine, through analogy, that visuo-spatial rehearsal may be selectively impaired by manual tapping which may reduce the overall IFR accuracy of visuo-spatial (but not verbal) stimuli and may selectively reduce the tendency to initiate recall with the first item, for visuo-spatial but not verbal lists.

On the generalizability of these effects to all episodic and semantic memory events

Although our findings seek to show similarities between verbal and visuo-spatial free recall, it could be argued that such findings are entirely to be expected; serial position functions in episodic memory are ubiquitous being observable with numerous different kinds of tests and stimuli over timespans from milliseconds (Neath & Crowder, 1996) to weeks and months (e.g., Baddeley & Hitch, 1977), and recency effects are clearly observable over years (e.g., Moreton & Ward, 2010; Rubin, 1982).

That such universal principles of memory exist has been championed by Surprenant and Neath (2009), who argued that serial position functions are a clear example of the *relative distinctiveness principle* – items will be well recalled to the extent to which they are more distinct than competing items at retrieval. To examine whether relative distinctiveness is a general principle, Neath (2010) provided evidence that serial position functions operate in both episodic and semantic memory. When participants are asked to recall the US presidents (e.g., Crowder, 1993; Roediger & Crowder, 1976; Healy, Havas, & Parker, 2000) they typically show primacy and recency effects, together with better recall for Abraham Lincoln. This finding was successfully modeled by Neath (2010) using both a temporal dimension and an item dimension (estimated by the number of Google page hits for each president). Neath and Saint-Aubin (2011) similarly observed primacy and recency effects in the free recall of Canadian prime ministers, and semantic serial position curves have also been observed using reconstruction of order tests. For example, Maylor (2002) found that serial position curves, similar to those obtained in episodic memory tests, were generated by regular church-goers using the six verses of well-known hymns as stimuli; Kelley, Neath, and Surprenant (2013) found characteristic bowed serial position curves using the lines of cartoon theme tunes, the order of Harry Potter books, sets of 9 Pixar movies, and the 9 top grossing movies from 2002-2010.

However, despite convincing evidence for serial position curves in semantic memory that resemble those in episodic memory, the tendency to initiate IFR of short lists with the first item is a relatively new phenomenon, and to our knowledge, has yet to be examined within semantic memory. If the output order in free recall of semantic events varied with the stimulus set (e.g., a tendency to start with the first of the four Indiana Jones movies; a tendency to start with one of the last four of the 23 James Bond movies) then this would provide further evidence for the *relative distinctiveness principle* and would constrain explanations for the finding.

Summary and Conclusion

We have presented four experiments that have compared verbal and non-verbal free recall, and these have led to two main sets of summary findings and conclusions. First, our experiments have shown that the tendency to initiate recall with the first item in a short list can be found with non-verbal stimuli such as visuo-spatial locations and touched facial locations, as well as with verbal lists. This finding demonstrates that this tendency is a general property of memory, and is not necessarily reliant on a verbal short-term memory or some other language- specific mechanism (albeit that verbal rehearsal may augment this tendency). Second, our experiments have shown that the patterns of IFR, the effects of list length, the order of recall, and their effects on the serial position curves show gross similarities between verbal and non-verbal stimuli. These findings are broadly consistent with functional equivalence between different stimulus domains. However, it is uncertain, at present, whether these similarities are best interpreted as demonstrating that both verbal and non-verbal stimuli are underpinned by common memory mechanisms, or whether similar but separate memory mechanisms are used in the recall of verbal and non-verbal stimuli. Our most recent data suggest that there are separate concurrent capacities for verbal and non-verbal stimuli, but the retrieval from the different stimulus domains appears not to be independent.

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Table 1A
Summary of the ANOVA tables from analyses conducted upon the proportion of correctly recalled items and the probability of first recall (PFR) data of Experiment 4.

	df	*MSE*	*F*	η^2_p	*p*
Proportion of items recalled FR Scoring					
AS	1,38	.009	136.3	.782	< .001
LL	10,380	.012	318.5	.893	< .001
Stimuli Group (SG)	1,38	.095	123.0	.764	< .001
AS x LL	10,380	.007	2.830	.069	.002
AS x SG	1,38	.009	80.43	.679	< .001
LL x SG	10,380	.012	13.50	.262	< .001
AS x LL x SG	10,380	.007	4.560	.107	< .001
The probability of first recall = SP1					
AS	1,38	.095	31.02	.449	< .001
LL	10,380	.049	119.1	.758	< .001
SG	1,38	.334	28.93	.432	< .001
AS x LL	10,380	.030	2.510	.062	.006
AS x SG	1,38	.095	16.32	.300	< .001
LL x SG	10,380	.049	4.640	.109	< .001
AS x LL x SG	10,380	.030	4.120	.098	< .001
The probability of first recall = Last 4					
AS	1,38	.096	37.18	.495	< .001
LL	9,342	.051	40.09	.518	< .001
SG	1,38	.578	13.09	.256	.001
AS x LL	9,342	.033	3.670	.088	< .001
AS x SG	1,38	.096	18.63	.329	< .001
LL x SG	9,342	.051	8.300	.179	< .001
AS x LL x SG	9,342	.033	2.131	.053	.027

Table 1B
Summary of the ANOVA tables from analyses conducted upon the proportion of correctly recalled items for both verbal and visuo-spatial groups respectively in Experiment 4.

	df	MSE	F	η^2_p	*p*
Proportion of words recalled FR Scoring					
AS	1,19	.010	195.9	.912	< .001
LL	10,190	.007	370.5	.951	< .001
AS x LL	10,190	.005	10.55	.357	< .001
Proportion of circles recalled FR Scoring					
AS	1,19	.008	4.010	.174	.060
LL	10,190	.170	83.26	.814	< .001
AS x LL	10,190	.010	.5011	.026	.888

Figure Captions

Figure 1. The overall accuracy data from all experiments. Figure 1A shows the effect of list length on the mean proportion of rounded rectangles (Experiment 1) and tactile presentations (Experiment 2) recalled, Figure 1B shows the effect of list length and AS on the mean proportion of rounded rectangles recalled in Experiment 3, and Figures 1C and 1D show the effect of list length and AS on the mean proportion of circles and words respectively recalled in Experiment 4.

Figure 2. The serial position curve data from Experiments 1 and 2. Figure 2A shows the serial position curves from lists of 1 to 15 rounded rectangles (Experiment 1). Figure 2B shows the serial position curves from lists of 1 to 15 tactile presentations (Experiment 2).

Figure 3. The Probability of First Recall (PFR) data from Experiments 1 and 2. Figure 3 show the proportion of trials in which recall initiated with the first word in the list (filled circles), one of the last four words on the list (filled triangles), or one of the other words in the list (grey squares). On a small minority of trials, participants began recall with an error (crosses). Figure 3A shows the recall of the rounded rectangles (data from Experiment 1); Figure 3B shows the recall of tactile presentations (data from Experiment 2).

Figure 4. The effect of the first recall on the serial position curves in Experiment 1 and Experiment 2. Panels 4A and 4D show the effect of initiating recall with the first stimulus in the list for Experiments 1 and 2, respectively. Panels 4B and 4E show the effect of initiating recall with one of the last four stimuli in the list for Experiments 1 and 2, respectively. Panels 4C and 4F show the effect of initiating recall with the first stimulus in the list for Experiments 1 and 2, respectively, with the data plotted using serial recall (SR) scoring.

Figure 5. The Lag-CRP (Conditionalised response probabilities) curves for each list length of each experimental condition. The data comes from the rounded rectangles of Experiment 1 (Figure 5A), the touched facial locations of Experiment 2 (Figure 5B), the No AS and AS rounded rectangles conditions of Experiment 3 (Figures 5C and 5D, respectively), and the No AS and AS circles, and No AS and AS words of Experiment 4 (Figures 5E – 5H, respectively). The lag refers to the difference in serial position between successive words recalled, such that smaller lags reflect the successive recall of words that were presented closer to each other on the list, and that positive values reflect pairs of words recalled in the same relative order as at presentation. The CRP represents the mean probability that a word of a particular lag was recalled. It is calculated by dividing the frequency of observed lag transitions by the number of legitimate opportunities in which words at each lag could be recalled.

Figure 6. Diagram of the experimental set up in Experiment 2. A set of 30 numbered stickers are attached to the participant's face (upper panel). The participant closes their eyes whilst the experimenter hears numbers through headphones, and touches the corresponding numbered locations using a cotton bud. At the end of the list, the participant clicks on the corresponding unnumbered locations of a schematic face that is presented on the computer screen (lower panel).

Figure 7. The serial position curve data from Experiments 3 and 4. Figures 7A and 7B shows the serial position curves from lists of 1 to 15 rounded rectangles presented in No AS and under AS conditions (Experiment 3). Figures 7C and 7D shows the serial position curves from lists of 1 to 15 circles presented in No AS and under AS conditions (Experiment 4). Figures 6E and 6F shows the serial position curves from lists of 1 to 15 visual words presented under No AS and AS conditions (Experiment 4).

Figure 8. The Probability of First Recall (PFR) data from Experiments 3 and 4. Figure 8 show the proportion of trials in which recall initiated with the first word in the list (filled circles), one of the last four words on the list (filled triangles), or one of the other words in the list (grey squares). On a small minority of trials, participants began recall with an error (crosses). Figures 8A and 8B shows the PFR data from lists of 1 to 15 rounded rectangles presented in No AS and under AS conditions (Experiment 3). Figures 8C and 8D shows the PFR data from lists of 1 to 15 circles presented in No AS and under AS conditions (Experiment 4). Figures 8E and 8F shows the PFR from lists of 1 to 15 visual words presented under No AS and AS conditions (Experiment 4).

Figure 9. The effect of the first recall on the serial position curves in Experiment 3. Panels 9A and 9B show the effect of initiating recall with the first stimulus in the list for the No AS and AS conditions of Experiment 3, respectively. Panels 8C and 8D show the effect of initiating recall with one of the last four stimuli in the list for the No AS and AS conditions of Experiment 3, respectively. Panels 9E and 9F show the effect of initiating recall with the first stimulus in the list for the No AS and AS conditions of Experiment 3, respectively, with the data plotted using serial recall (SR) scoring.

Figure 10. The effect of the first circle recalled on the recall of serial position curves of the lists of circles in Experiment 4. Panels 10A and 10B show the effect of initiating recall with the first circle in the list for the No AS and AS conditions of Experiment 4, respectively. Panels 10C and 10D show the effect of initiating recall with one of the last four circles in the list for the No AS and AS conditions of Experiment 4, respectively. Panels 10E and 10F show the effect of initiating recall with the first circle in the list for the No AS and AS conditions of Experiment 4, respectively, with the data plotted using serial recall (SR) scoring.

Figure 11. The effect of the first word recalled on the recall of serial position curves of the lists of words in Experiment 4. Panels 11A and 11B show the effect of initiating recall with the first word in the list for the No AS and AS conditions of Experiment 4, respectively. Panels 11C and 11D show the effect of initiating recall with one of the last four words in the list for the No AS and AS conditions of Experiment 4, respectively. Panels 11E and 11F show the effect of initiating recall with the first word in the list for the No AS and AS conditions of Experiment 4, respectively, with the data plotted using serial recall (SR) scoring.

Figure 1

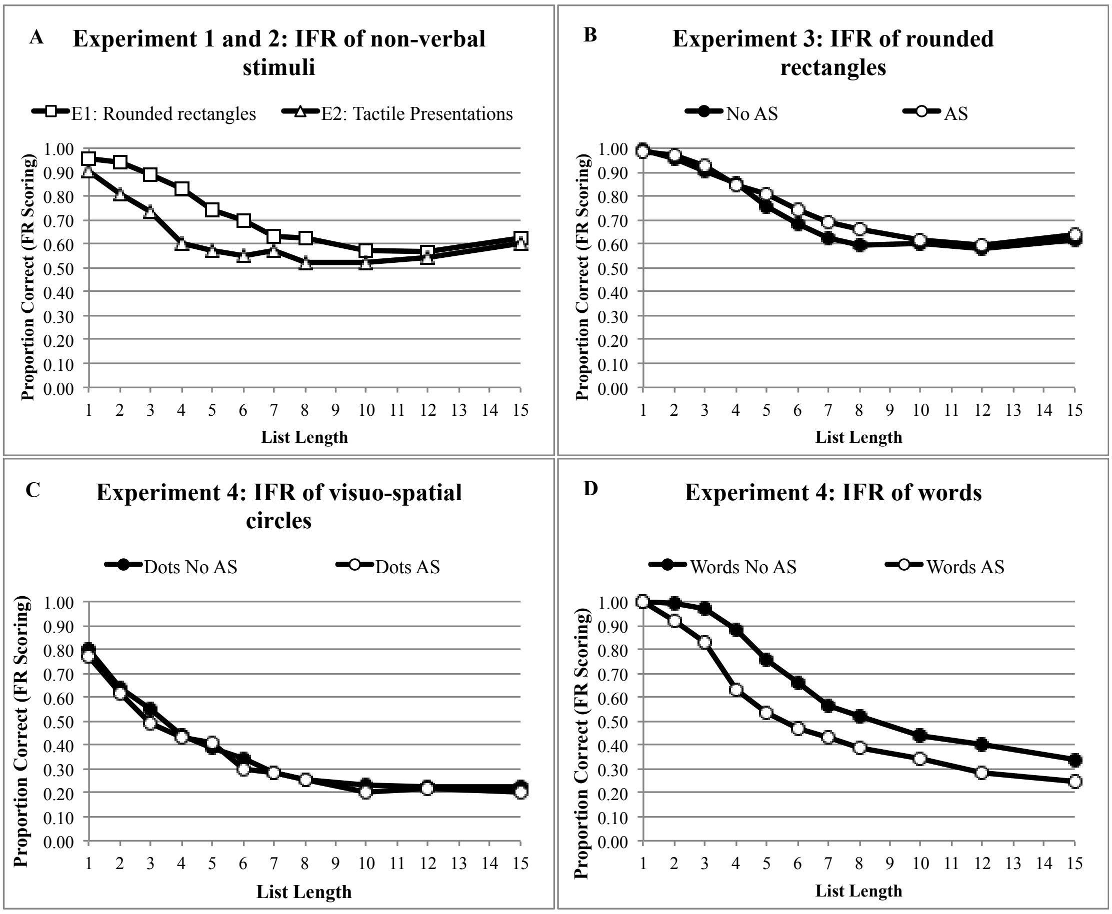
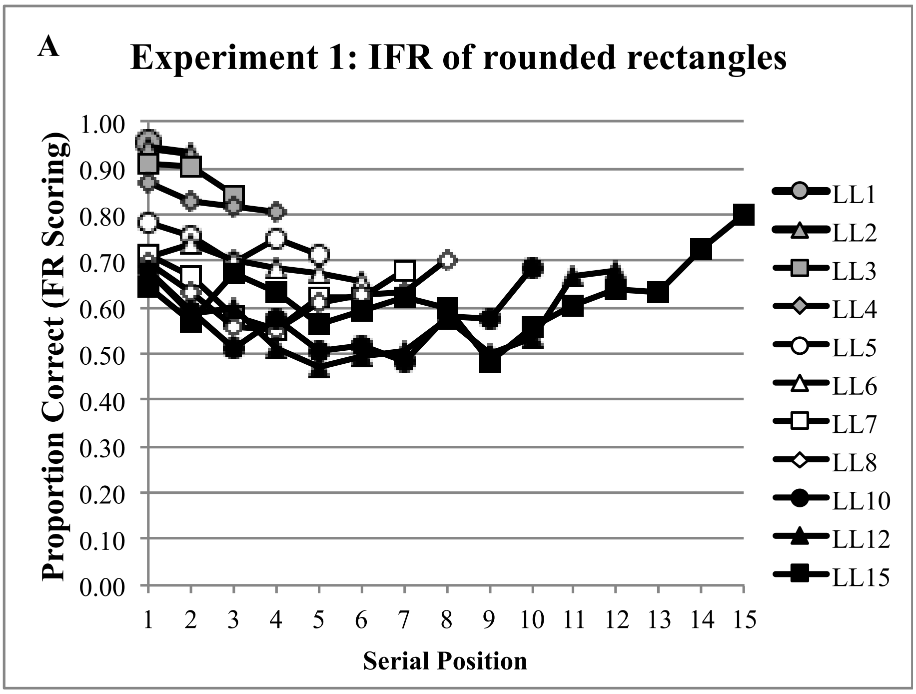

A
Experiment 1 and 2: IFR of non-verbal stimuli
E1: Rounded rectangles
E2: Tactile Presentations
Proportion Correct (FR Scoring)
List Length
B
Experiment 3: IFR of rounded rectangles
No AS
AS
Proportion Correct (FR Scoring)
List Length
C
Experiment 4: IFR of visuo-spatial circles
Dots No AS
Dots AS
Proportion Correct (FR Scoring)
List Length
D
Experiment 4: IFR of words
Words No AS
Words AS
Proportion Correct (FR Scoring)
List Length

Figure 2


A
Experiment 1: IFR of rounded rectangles
Proportion Correct (FR Scoring)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Serial Position
LL1
LL2
LL3
LL4
LL5
LL6
LL7
LL8
LL10
LL12
LL15

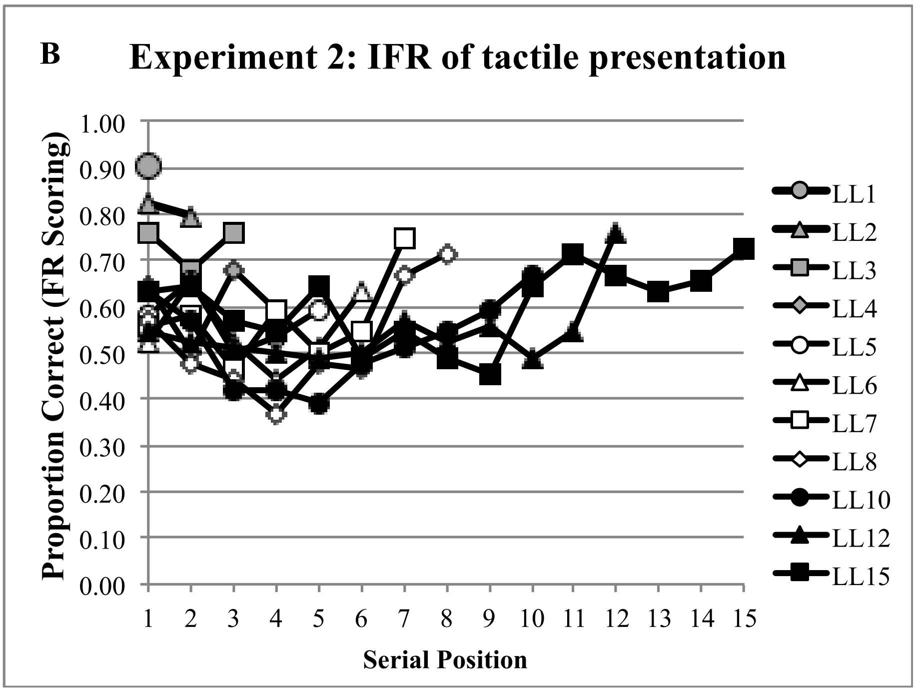

B
Experiment 2: IFR of tactile presentation
Proportion Correct (FR Scoring)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Serial Position
LL1
LL2
LL3
LL4
LL5
LL6
LL7
LL8
LL10
LL12
LL15

Figure 3

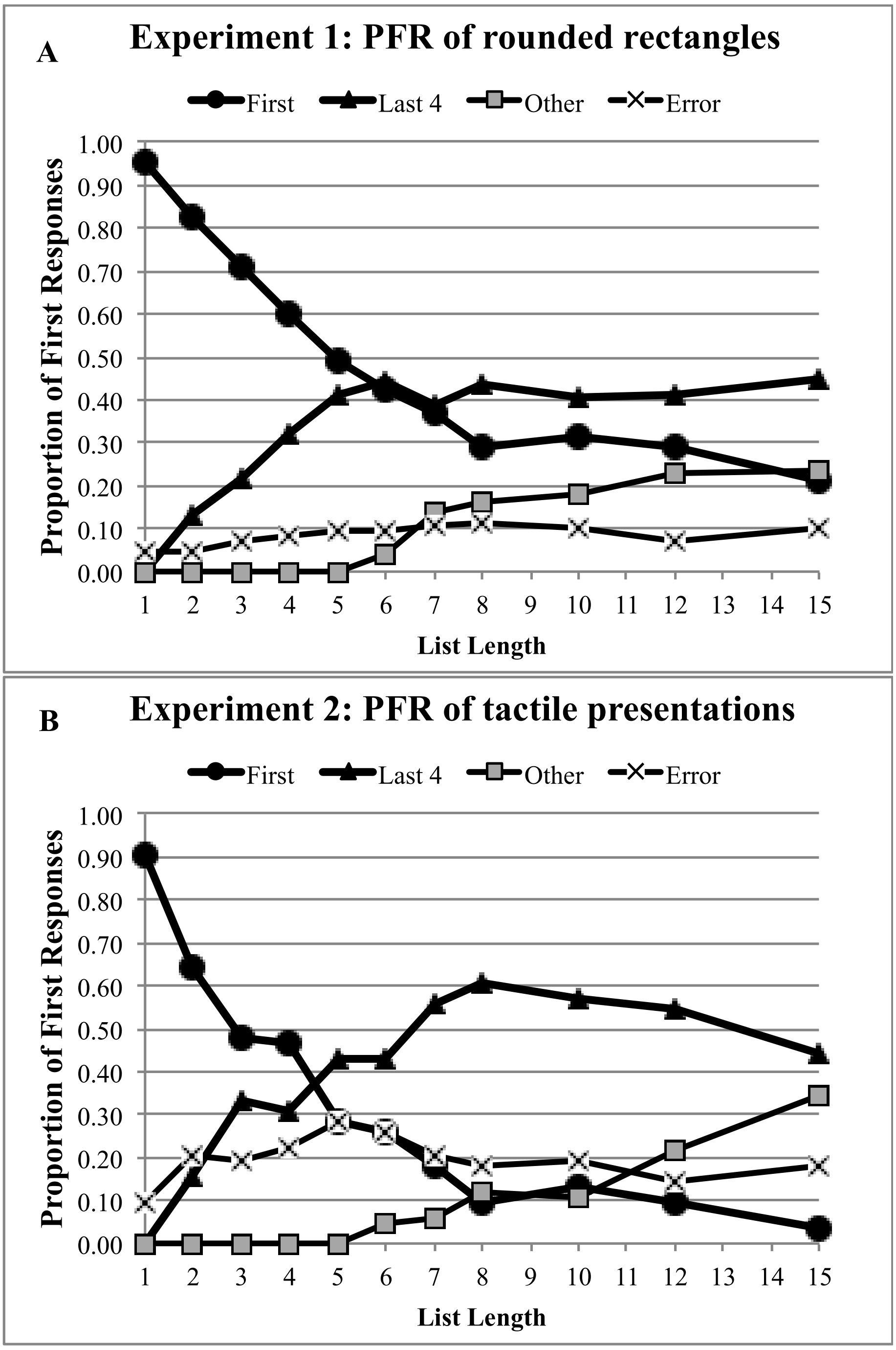

A
Experiment 1: PFR of rounded rectangles
First
Last 4
Other
Error
Proportion of First Responses
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
List Length
B
Experiment 2: PFR of tactile presentations
First
Last 4
Other
Error
Proportion of First Responses
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
List Length

Figure 4

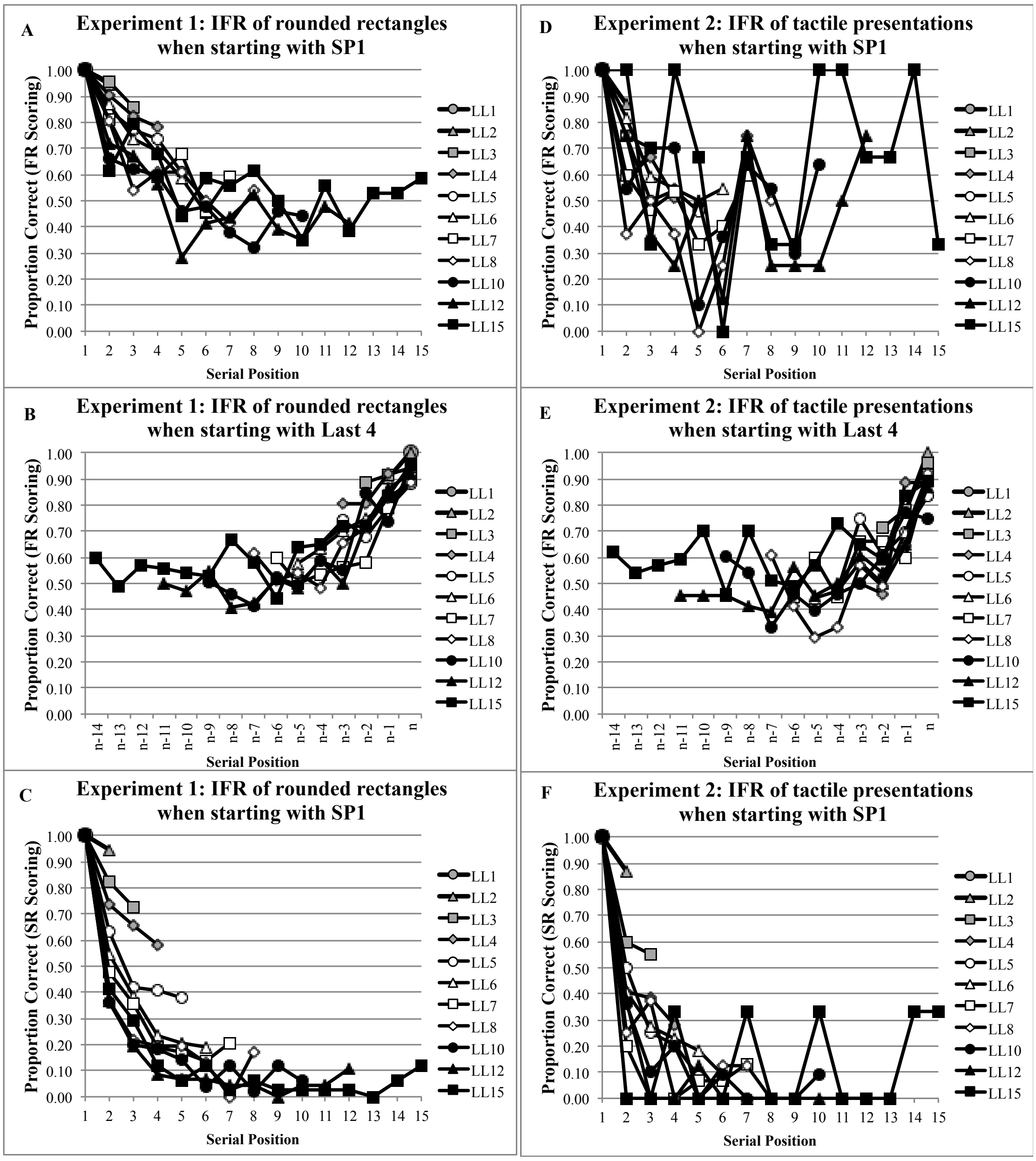
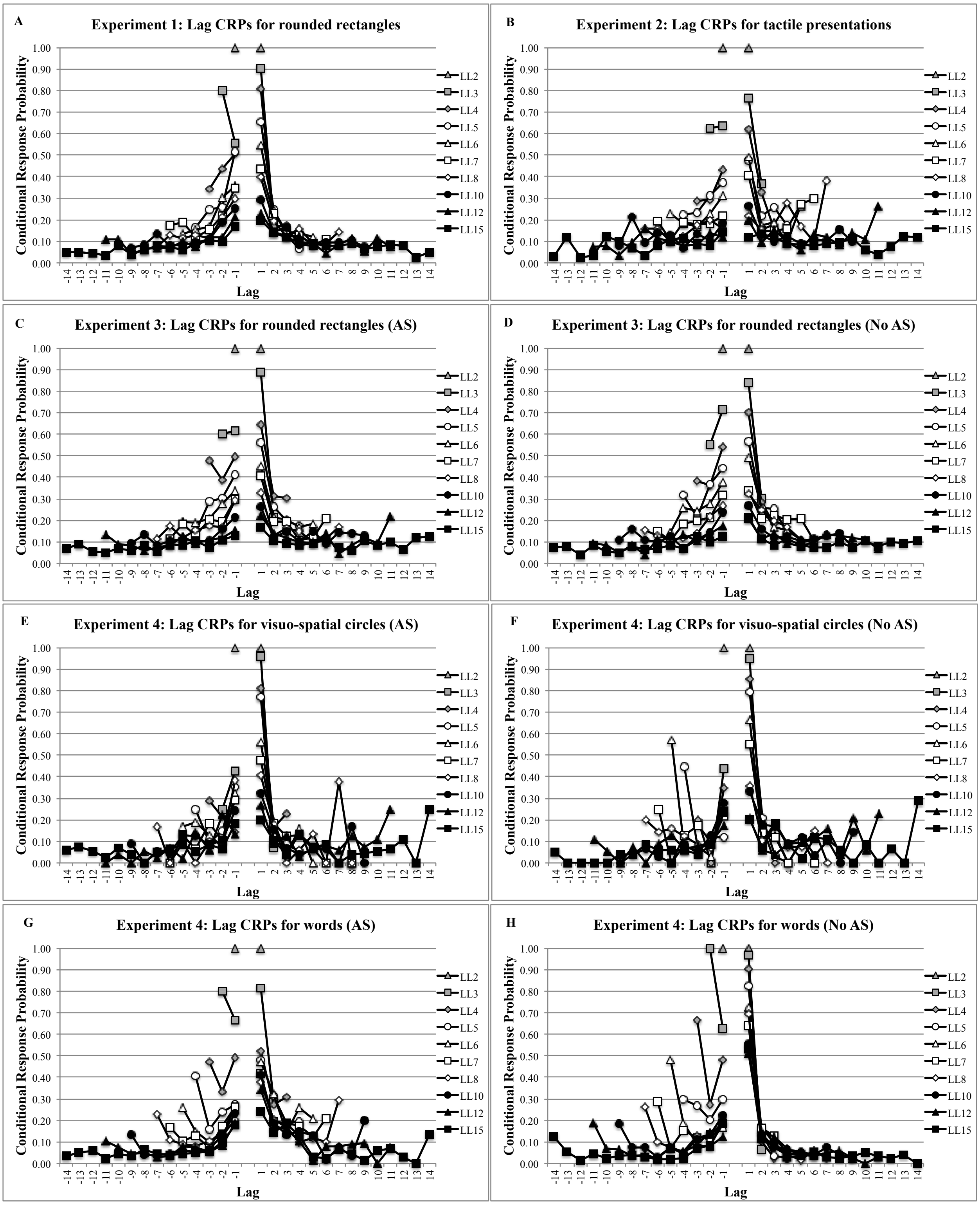


Figure 5


A
Experiment 1: Lag CRPs for rounded rectangles
B
Experiment 2: Lag CRPs for tactile presentations
C
Experiment 3: Lag CRPs for rounded rectangles (AS)
D
Experiment 3: Lag CRPs for rounded rectangles (No AS)
E
Experiment 4: Lag CRPs for visuo-spatial circles (AS)
F
Experiment 4: Lag CRPs for visuo-spatial circles (No AS)
G
Experiment 4: Lag CRPs for words (AS)
H
Experiment 4: Lag CRPs for words (No AS)
Conditional Response Probability
Lag
LL2
LL3
LL4
LL5
LL6
LL7
LL8
LL10
LL12
LL15

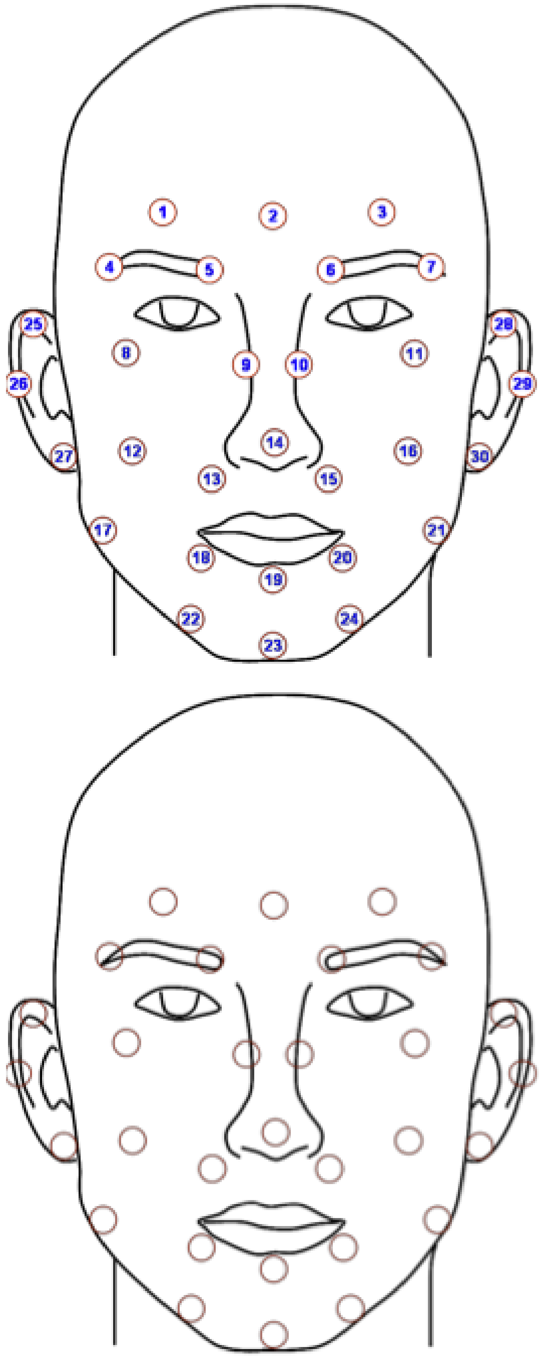

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Figure 6

Figure 7

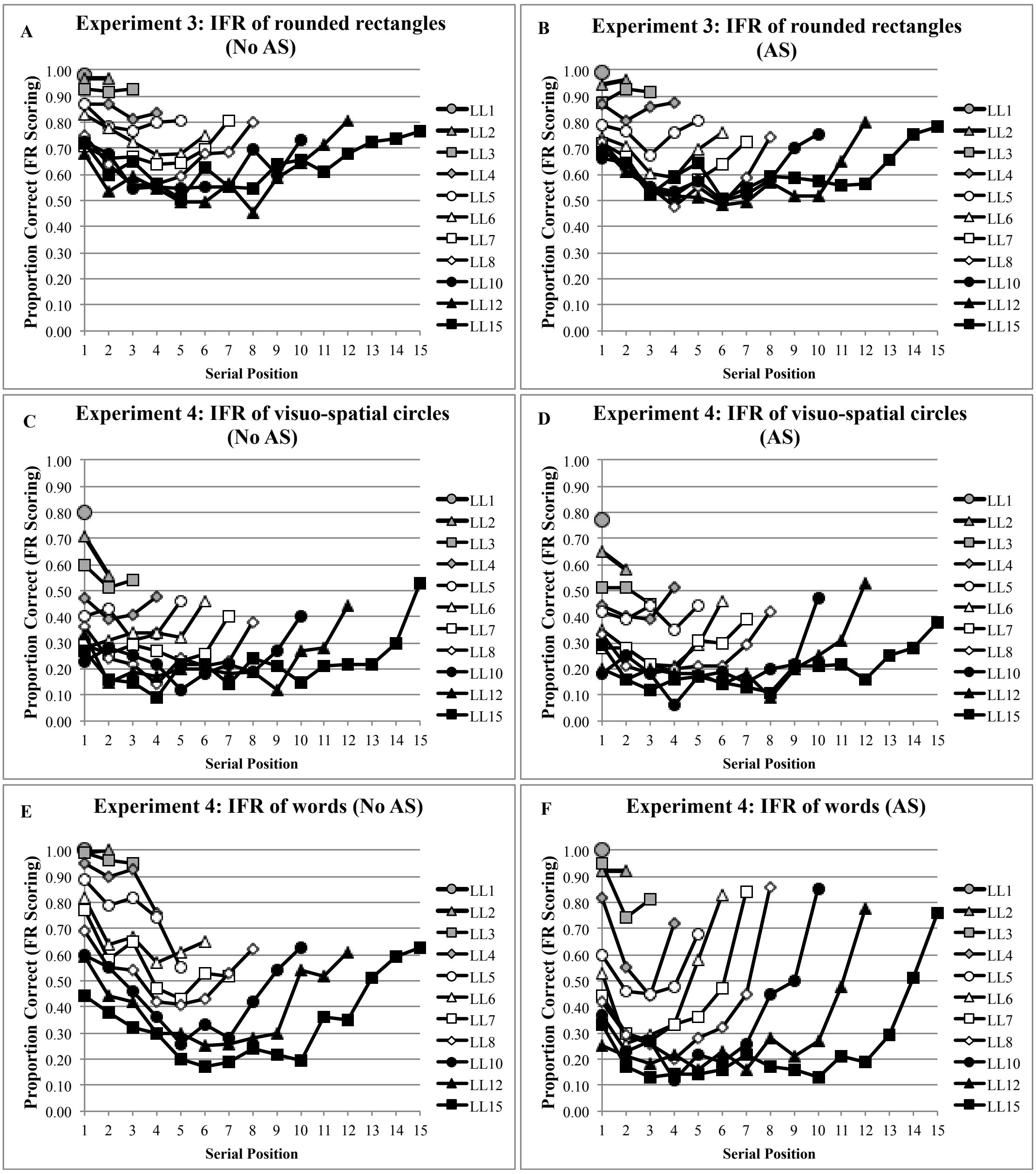

A
Experiment 3: IFR of rounded rectangles (No AS)
B
Experiment 3: IFR of rounded rectangles (AS)
C
Experiment 4: IFR of visuo-spatial circles (No AS)
D
Experiment 4: IFR of visuo-spatial circles (AS)
E
Experiment 4: IFR of words (No AS)
F
Experiment 4: IFR of words (AS)
Proportion Correct (FR Scoring)
Serial Position
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
LL1
LL2
LL3
LL4
LL5
LL6
LL7
LL8
LL10
LL12
LL15

Figure 8

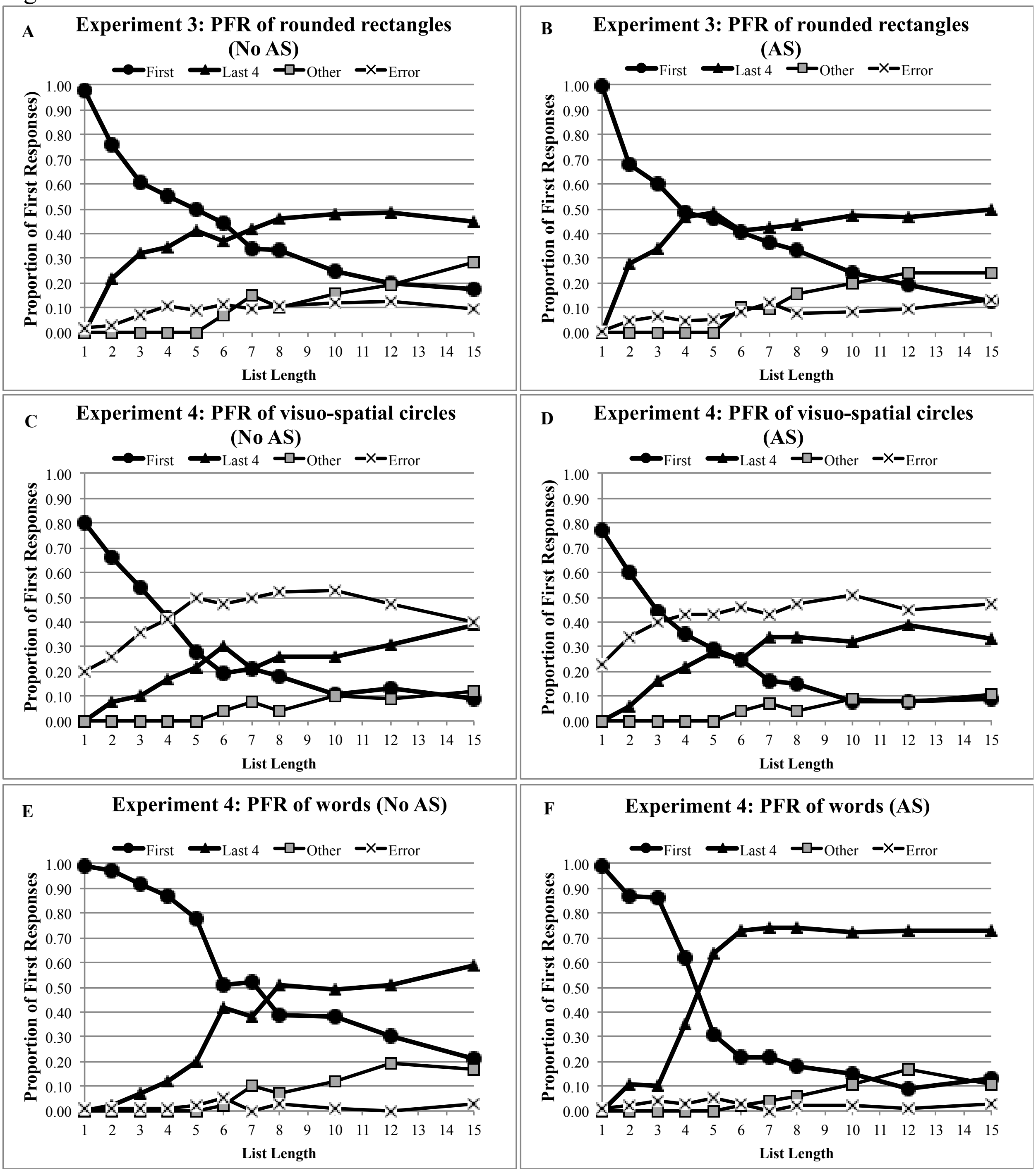

A
Experiment 3: PFR of rounded rectangles (No AS)
First
Last 4
Other
Error
Proportion of First Responses)
List Length
B
Experiment 3: PFR of rounded rectangles (AS)
Proportion of First Responses
C
Experiment 4: PFR of visuo-spatial circles (No AS)
D
Experiment 4: PFR of visuo-spatial circles (AS)
E
Experiment 4: PFR of words (No AS)
F
Experiment 4: PFR of words (AS)

Figure 9

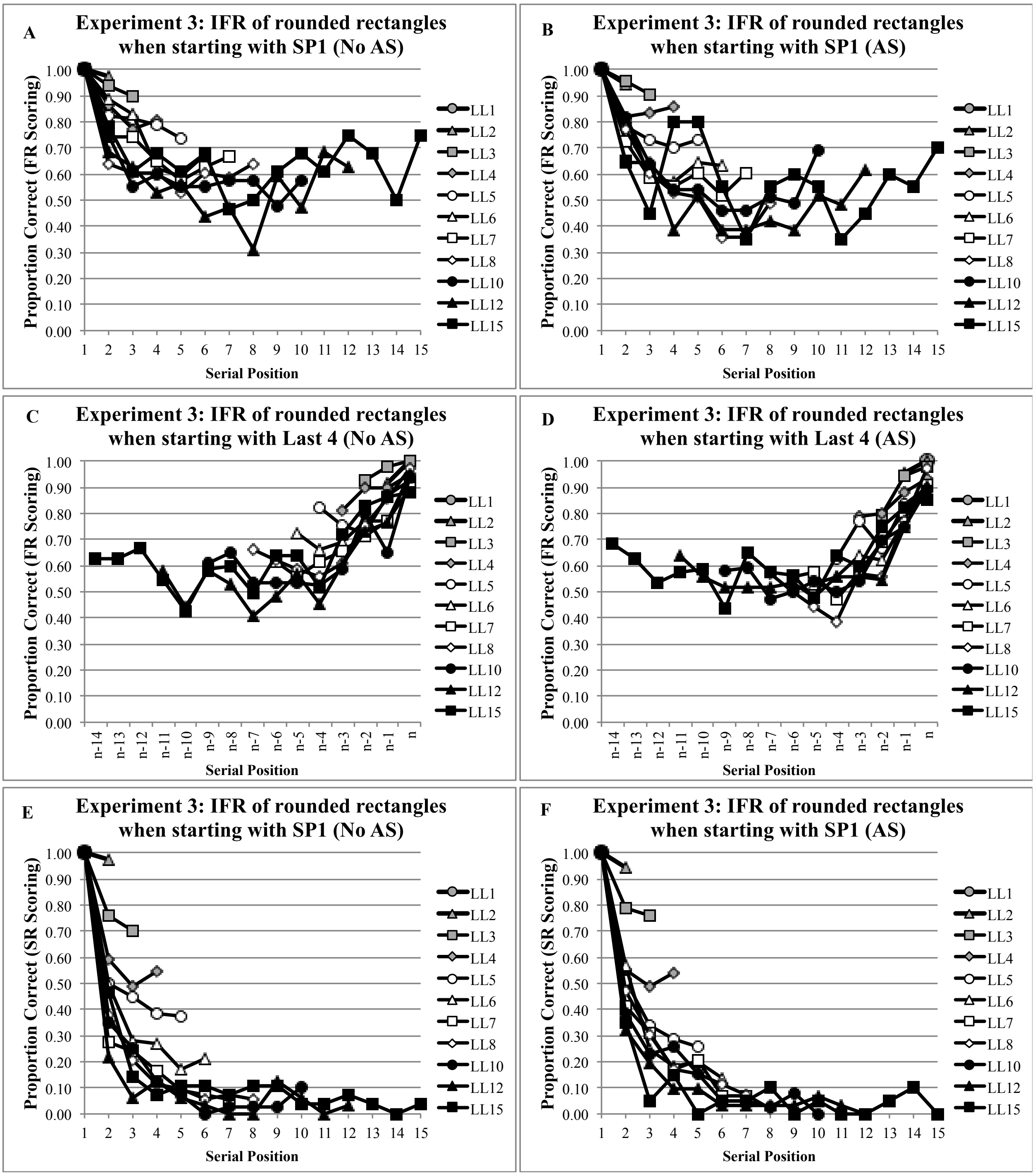

A
Experiment 3: IFR of rounded rectangles when starting with SP1 (No AS)
Proportion Correct (FR Scoring)
Serial Position
LL1
LL2
LL3
LL4
LL5
LL6
LL7
LL8
LL10
LL12
LL15
B
Experiment 3: IFR of rounded rectangles when starting with SP1 (AS)
Proportion Correct (FR Scoring)
Serial Position
C
Experiment 3: IFR of rounded rectangles when starting with Last 4 (No AS)
Proportion Correct (FR Scoring)
Serial Position
D
Experiment 3: IFR of rounded rectangles when starting with Last 4 (AS)
Proportion Correct (FR Scoring)
Serial Position
E
Experiment 3: IFR of rounded rectangles when starting with SP1 (No AS)
Proportion Correct (SR Scoring)
Serial Position
F
Experiment 3: IFR of rounded rectangles when starting with SP1 (AS)
Proportion Correct (SR Scoring)
Serial Position

Figure 10

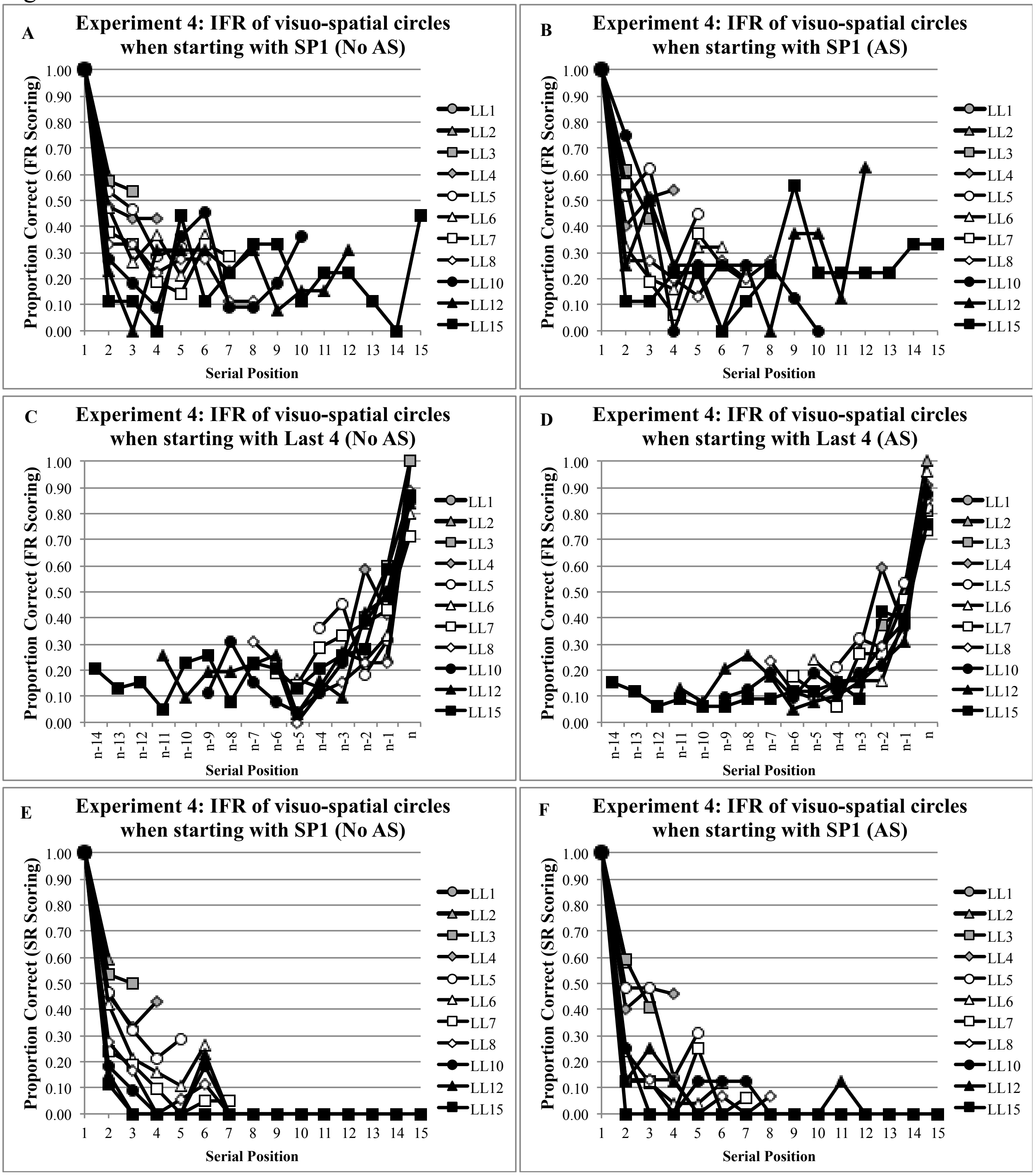
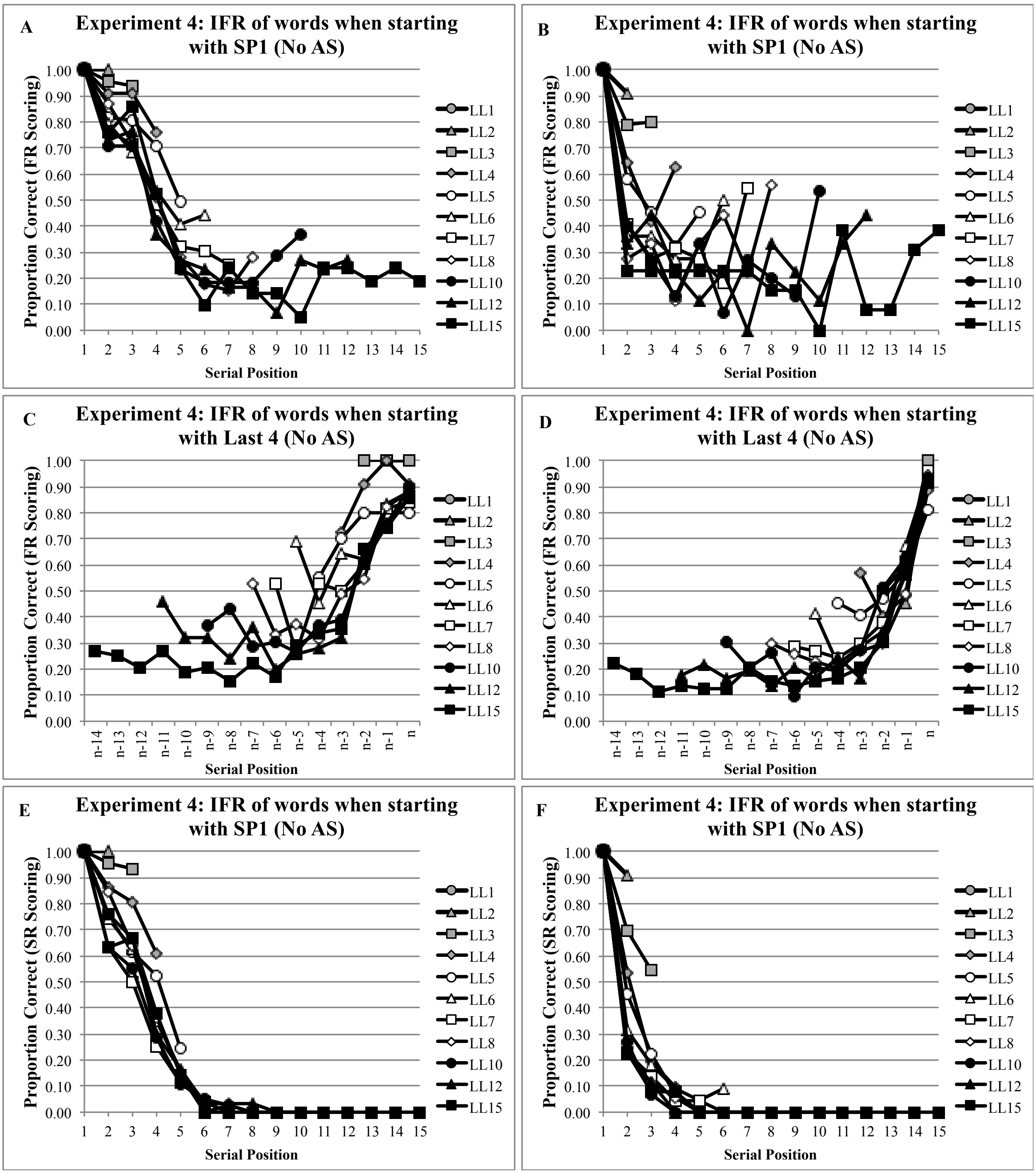


Figure 11


A
Experiment 4: IFR of words when starting with SP1 (No AS)
Proportion Correct (FR Scoring)
Serial Position
B
Experiment 4: IFR of words when starting with SP1 (No AS)
Proportion Correct (FR Scoring)
Serial Position
C
Experiment 4: IFR of words when starting with Last 4 (No AS)
Proportion Correct (FR Scoring)
Serial Position
D
Experiment 4: IFR of words when starting with Last 4 (No AS)
Proportion Correct (FR Scoring)
Serial Position
E
Experiment 4: IFR of words when starting with SP1 (No AS)
Proportion Correct (SR Scoring)
Serial Position
F
Experiment 4: IFR of words when starting with SP1 (No AS)
Proportion Correct (SR Scoring)
Serial Position
LL1
LL2
LL3
LL4
LL5
LL6
LL7
LL8
LL10
LL12
LL15

Appendix A: Analysis of Serial Position Curves

Appendix A1: Analysis from Experiment 1

Table A1 - Analyses of the IFR serial position curves from Experiment 1, shown in Figure 2A, using all the data with FR scoring. At each list length, the IFR data were subjected to a repeated measures ANOVA to show the main effect of Serial Position

List Length	Main effect of Serial Position
2	$F(1,19) = .241$, $p = .629$, $\eta^2_p = 0.012$, $MSE = .006$
3	$F(2,38) = 2.82$, $p = .072$, $\eta^2_p = 0.129$, $MSE = .010$
4	$F(3,57) = 1.23$, $p = .307$, $\eta^2_p = 0.061$, $MSE = .012$
5	$F(4,76) = .997$, $p = .415$, $\eta^2_p = 0.050$, $MSE = .025$
6	$F(5,95) = .497$, $p = .778$, $\eta^2_p = 0.025$, $MSE = .031$
7	**$F(6,114) = 2.27$, $p = .041$, $\eta^2_p = 0.107$, $MSE = .029$**
8	$F(7,133) = 1.79$, $p = .094$, $\eta^2_p = 0.086$, $MSE = .033$
10	**$F(9,171) = 2.31$, $p = .018$, $\eta^2_p = 0.108$, $MSE = .043$**
12	**$F(11,209) = 2.81$, $p = .002$, $\eta^2_p = 0.129$, $MSE = .042$**
15	**$F(14,266) = 3.58$, $p < .001$, $\eta^2_p = 0.158$, $MSE = .031$**

Note: significant main effects are presented in bold

Appendix A2: Analysis from Experiment 2

Table A2 - Analyses of the IFR serial position curves from Experiment 2, shown in Figure 2B, using all the data with FR scoring. At each list length, the IFR data were subjected to a repeated measures ANOVA to show the main effect of Serial Position

List Length	Main effect of Serial Position
2	$F(1,20) = .214$, $p = .649$, $\eta^2_p = 0.011$, $MSE = .028$
3	$F(2,40) = .854$, $p = .854$, $\eta^2_p = 0.041$, $MSE = .057$
4	$F(3,60) = 2.70$, $p = .054$, $\eta^2_p = 0.119$, $MSE = .047$
5	$F(4,80) = 1.135$, $p = .346$, $\eta^2_p = 0.054$, $MSE = .065$
6	$F(5,100) = 1.677$, $p = .147$, $\eta^2_p = 0.077$, $MSE = .081$
7	**$F(6,120) = 3.16$, $p = .007$, $\eta^2_p = 0.136$, $MSE = .055$**
8	**$F(7,140) = 4.986$, $p < .001$, $\eta^2_p = 0.200$, $MSE = .038$**
10	**$F(9,180) = 2.774$, $p = .005$, $\eta^2_p = 0.122$, $MSE = .069$**
12	$F(11,220) = 1.674$, $p = .081$, $\eta^2_p = 0.077$, $MSE = .069$
15	**$F(14,280) = 2.55$, $p = .002$, $\eta^2_p = 0.113$, $MSE = .057$**

Note: significant main effects are presented in bold

Appendix A3: Analysis from Experiment 3

Table A3. Analyses of the IFR serial position curves from Experiment 3, shown in Figures 7A and 7B, using all the data with FR scoring. At each list length, the IFR data were subjected to a 2 (AS and No AS group) x *n* (serial position: SP, 1, …, *n*) mixed ANOVA, where *n* refers here, and throughout the Appendices, to the list length.

List length	Main Effects		Interaction
	Articulatory suppression	Serial position	
2	F (1,38) = 1.04, p = .313, η^2_p= .027, *MSE*=.005	F (1,38) = .322, p = .574, η^2_p = .008, *MSE*=.005	F (1,38) = .322, p = .574, η^2_p = .008, *MSE*=.005
3	F (1,38) = .581, p = .451, η^2_p= .015, *MSE*=.016	F (2,76) = .687, p = .506, η^2_p= .018, *MSE*=.010	F (2,76) = .873, p = .422, η^2_p= .022, *MSE*=.010
4	F (1,38) = .114, p = .737, η^2_p= .003, *MSE*=.016	F (3,114) = .606, p = .612, η^2_p= .016, *MSE*=.020	F (3,114) = 1.28, p = .284, η^2_p= .033, *MSE*=.020
5	F (1,38) = 2.21, p = .145, η^2_p= .055, *MSE*=.051	**F (4,152) = 2.65, p = .035, η^2_p= .065, *MSE*=.022**	F (4,152) = .929, p = .449, η^2_p= .024, *MSE*=.022
6	F (1,38) = 3.81, p = .059, η^2_p= .091, *MSE*=.042	**F (5,190) = 4.71, p < .001, η^2_p= .110, *MSE*=.031**	F (5,190) = 1.03, p =.400, η^2_p= .026, *MSE*=.031
7	F (1,38) = 3.39, p = .073, η^2_p= .082, *MSE*=.063	**F (6,228) = 5.97, p < .001, η^2_p= .136, *MSE*=.030**	F (6,228) = .858, p =.527, η^2_p= .022, *MSE*=.030
8	**F (1,38) = 4.64, p = .038, η^2_p= .109, *MSE*=.061**	**F (7,266) = 9.40, p < .001, η^2_p= .198, *MSE*=.033**	F (7,266) = .990, p =.439, η^2_p= .025, *MSE*=.033
10	F (1,38) = .249, p = .621, η^2_p= .007, *MSE*=.054	**F (9,342) = 7.01, p < .001, η^2_p= .156, *MSE*=.034**	F (9,342) = .970, p =.464, η^2_p= .025, *MSE*=.034
12	F (1,38) = .214, p = .646, η^2_p= .006, *MSE*=.053	**F (11,418) = 10.1, p < .001, η^2_p=.210, *MSE*=.034**	F (11,418) = 1.19, p=.290, η^2_p=.030, *MSE*=.034
15	F (1,38) = 1.96, p = .170, η^2_p= .049, *MSE*=.039	**F (14,532) = 6.28, p < .001, η^2_p= .142, *MSE*=.030**	**F (14,532) = 1.74, p=.044, η^2_p= .044, *MSE*=.030**

Note: significant main effects and interactions are presented in bold

Appendix A4: Analysis from Experiment 4

Table A4. Analyses of the IFR serial position curves from Experiment 4, shown in Figures 7C-7F, using all the data with FR scoring. At each list length, the IFR data were subjected to a 2 (AS and No AS group) x *n* (serial position: SP, 1, …, n) mixed ANOVA. This was done separately for both the visuo-spatial (Figures 7C and 7D) and verbal (Figures 7E and 7F) groups.

List length	Main Effects		Interaction
	Articulatory suppression	Serial position	
Visuo-Spatial			
2	$F(1,19) = .134, p = .718, \eta^2_p = .007, MSE = .060$	$F(1,19) = 3.07, p = .096, \eta^2_p = .139, MSE = .079$	$F(1,19) = 1.03, p = .322, \eta^2_p = .052, MSE = .031$
3	$F(1,19) = 3.53, p = .083, \eta^2_p = .150, MSE = .032$	$F(2,38) = .471, p = .628, \eta^2_p = .024, MSE = .083$	$F(2,38) = .962, p = .391, \eta^2_p = .048, MSE = .028$
4	$F(1,19) = .005, p = .945, \eta^2_p < .001, MSE = .051$	$F(3,57) = 2.36, p = .081, \eta^2_p = .111, MSE = .038$	$F(3,57) = .151, p = .929, \eta^2_p = .008, MSE = .050$
5	$F(1,19) = .584, p = .454, \eta^2_p = .030, MSE = .041$	$F(4,76) = 1.13, p = .350, \eta^2_p = .056, MSE = .061$	$F(4,76) = .830, p = .510, \eta^2_p = .042, MSE = .052$
6	$F(1,19) = 3.72, p = .069, \eta^2_p = .164, MSE = .026$	**$F(5,95) = 3.52, p = .006, \eta^2_p = .156, MSE = .055$**	$F(5,95) = 1.18, p = .324, \eta^2_p = .059, MSE = .048$
7	$F(1,19) = .044, p = .836, \eta^2_p = .002, MSE = .029$	**$F(6,114) = 2.91, p = .011, \eta^2_p = .133, MSE = .038$**	$F(6,114) = .654, p = .687, \eta^2_p = .033, MSE = .050$
8	$F(1,19) = .038, p = .847, \eta^2_p = .002, MSE = .029$	**$F(7,133) = 4.67, p < .001, \eta^2_p = .197, MSE = .053$**	$F(7,133) = .513, p = .824, \eta^2_p = .026, MSE = .036$
10	**$F(1,19) = 6.10, p = .023, \eta^2_p = .243, MSE = .014$**	**$F(9,171) = 7.97, p < .001, \eta^2_p = .296, MSE = .036$**	$F(9,171) = 1.49, p = .154, \eta^2_p = .073, MSE = .030$
12	$F(1,19) = .477, p = .498, \eta^2_p = .025, MSE = .017$	**$F(11,209) = 7.18, p < .001, \eta^2_p = .274, MSE = .051$**	$F(11,209) = 1.52, p = .125, \eta^2_p = .074, MSE = .028$
15	$F(1,19) = 2.82, p = .109, \eta^2_p = .129, MSE = .026$	**$F(14,266) = 7.61, p < .001, \eta^2_p = .286, MSE = .036$**	$F(14,266) = 1.24, p = .243, \eta^2_p = .061, MSE = .031$
Verbal			
2	**$F(1,19) = 12.0, p = .003, \eta^2_p = .388, MSE = .009$**	$F(1,19) = .038, p = .847, \eta^2_p = .002, MSE = .013$	$F(1,19) = .023, p = .881, \eta^2_p = .001, MSE = .022$
3	**$F(1,19) = 36.2, p < .001, \eta^2_p = .656, MSE = .015$**	**$F(2,38) = 6.39, p = .004, \eta^2_p = .252, MSE = .024$**	**$F(2,38) = 5.68, p = .007, \eta^2_p = .230, MSE = .014$**
4	**$F(1,19) = 59.4, p < .001, \eta^2_p = .758, MSE = .043$**	**$F(3,57) = 6.16, p = .001, \eta^2_p = .245, MSE = .049$**	**$F(3,57) = 10.2\ p < .001, \eta^2_p = .349, MSE = .041$**
5	**$F(1,19) = 39.1, p < .001, \eta^2_p = .673, MSE = .064$**	**$F(4,76) = 2.70, p = .037, \eta^2_p = .124, MSE = .047$**	**$F(4,76) = 7.77\ p < .001, \eta^2_p = .290, MSE = .053$**
6	**$F(1,19) = 48.6, p < .001, \eta^2_p = .719, MSE = .045$**	**$F(5,95) = 7.84, p < .001, \eta^2_p = .292, MSE = .079$**	**$F(5,95) = 10.8, p < .001, \eta^2_p = .362, MSE = .046$**
7	**$F(1,19) = 49.3, p < .001, \eta^2_p = .722, MSE = .026$**	**$F(6,114) = 6.14, p < .001, \eta^2_p = .244, MSE = .076$**	**$F(6,114) = 8.30, p < .001, \eta^2_p = .304, MSE = .067$**
8	**$F(1,19) = 86.7, p < .001, \eta^2_p = .820, MSE = .018$**	**$F(7,133) = 9.37, p < .001, \eta^2_p = .330, MSE = .083$**	**$F(7,133) = 4.28, p < .001, \eta^2_p = .184, MSE = .069$**
10	**$F(1,19) = 40.2, p = .023, \eta^2_p = .679, MSE = .023$**	**$F(9,171) = 13.8, p < .001, \eta^2_p = .421, MSE = .073$**	**$F(9,171) = 5.19\ p < .001, \eta^2_p = .215, MSE = .049$**
12	**$F(1,19) = 32.6, p < .001, \eta^2_p = .631, MSE = .049$**	**$F(11,209) = 11.3, p < .001, \eta^2_p = .373, MSE = .071$**	**$F(11,209) = 4.66, p < .001, \eta^2_p = .197, MSE = .042$**
15	**$F(1,19) = 19.0, p < .001, \eta^2_p = .500, MSE = .067$**	**$F(14,266) = 16.9, p < .001, \eta^2_p = .470, MSE = .056$**	**$F(14,266) = 2.30, p = .005, \eta^2_p = .108, MSE = .040$**

Note: significant main effects and interactions are presented in bold

Appendix B: Analysis of Serial Position Curves when P(FR=SP1)

Appendix B1: Analysis from Experiment 1

Table B1 - Analyses of the IFR serial position curves from Experiment 1, shown in Figure 4A, using only data from trials starting with SP1 using FR scoring. At each list length, the free recall data were subjected to a repeated measures ANOVA. Note that there were relatively few participants included in the analyses at longer list lengths.

List Length	Main effect of Serial Position
3 $N = 20$	$F(1,19) = 3.58$, $p = .074$, $\eta^2_p = .158$, $MSE = .017$
4 $N = 20$	$F(2,38) = .928$, $p = .404$, $\eta^2_p = .047$, $MSE = .046$
5 $N = 20$	**$F(3,57) = 4.02$, $p = .012$, $\eta^2_p = .175$, $MSE = .069$**
6 $N = 18$	**$F(4,68) = 5.60$, $p = .001$, $\eta^2_p = .248$, $MSE = .077$**
7 $N = 16$	$F(5,75) = 1.80$, $p = .122$, $\eta^2_p = .107$, $MSE = .109$
8 $N = 16$	$F(6,90) = 1.84$, $p = .101$, $\eta^2_p = .109$, $MSE = .105$
10 $N = 15$	$F(8,112) = 1.25$, $p = .277$, $\eta^2_p = .082$, $MSE = .103$
12 $N = 11$	**$F(10,100) = 2.59$, $p = .008$, $\eta^2_p = .206$, $MSE = .080$**
15 $N = 11$	**$F(13,130) = 2.07$, $p = .020$, $\eta^2_p = .171$, $MSE = .115$**

Note: significant main effects are presented in bold

Appendix B2: Analysis from Experiment 2

Table B2 - Analyses of the IFR serial position curves from Experiment 2, shown in Figure 4D, using only data from trials starting with SP1 using FR scoring. At each list length, the free recall data were subjected to a repeated measures ANOVA. Note that there were relatively few participants included in the analyses at longer list lengths.

List Length	Main effect of Serial Position
3 $N = 18$	$F(1,17) = .150$, $p = .704,4$ $\eta^2_p = .009$, $MSE = .129$
4 $N = 18$	$F(2,34) = 1.14$, $p = .332$, $\eta^2_p = .063$, $MSE = .119$
5 $N = 14$	$F(3,39) = 2.65$, $p = .062$, $\eta^2_p = .169$, $MSE = .145$
6 $N = 12$	$F(4,44) = .857$, $p = .497$, $\eta^2_p = .072$, $MSE = .200$
7 $N = 11$	$F(5,50) = .781$, $p = .568$, $\eta^2_p = .072$, $MSE = .206$
8 $N = 8$	$F(6,42) = 1.78$, $p = .127$, $\eta^2_p = .203$, $MSE = .244$
10 $N = 7$	$F(8,48) = 1.07$, $p = .403$, $\eta^2_p = .151$, $MSE = .225$
12 $N = 7$	$F(10,60) = 1.18$, $p = .323$, $\eta^2_p = .164$, $MSE = .253$
15 $N = 3$	$F(13,26) = 1.76$, $p = .107$, $\eta^2_p = .468$, $MSE = .189$

Note: significant main effects are presented in bold

Appendix B3: Analysis from Experiment 3

Table B3. Analyses of the IFR serial position curves from Experiment 3, shown in Figures 9A and 9B, using only data from trials starting with SP1 with FR scoring. At each list length, the free recall data were subjected to a 2 (group: AS and No AS) x n – 1 (serial position: SP, 2, …,n) mixed ANOVA.. Note that there were relatively few participants included in the analysis at longer list lengths.

List length	Main Effects		Interaction
	Articulatory suppression	Serial position	
3 AS = 20; S = 19	F (1,37)=.037, p = .849, η^2_p= .001, MSE= .017	F (1,37) = 3.88, p = .056, η^2_p= .095, MSE= .021	F (1,37) = .312, p = .580, η^2_p= .008, MSE= .021
4 AS = 20; S = 20	F (1,38) =1.72, p = .197, η^2_p= .043, MSE= .052	F (2,76) = .413, p = .663, η^2_p= .011, MSE= .037	F (2,76) = .402, p = .671, η^2_p= .010, MSE= .037
5 AS = 18; S = 19	F (1,35) = .627, p = .434, η^2_p= .018, MSE= .080	F (3,105) = .725, p = .539, η^2_p= .020, MSE= .040	F (3,105) = .245, p = .865, η^2_p= .007, MSE= .040
6 AS = 17; S = 20	F (1,35) = 3.88, p = .057, η^2_p= .100, MSE= .070	**F (4,140) = 3.75, p = .006, η^2_p= .097**, MSE= .081	F (4,140) = 1.19, p = .319, η^2_p= .033, MSE= .081
7 AS = 17; S = 18	F (1,33) = 3.92, p = .056, η^2_p= .106, MSE= .127	F (5,165) = 1.81, p = .114, η^2_p= .052, MSE= .102	F (5,165) = 1.74, p = .127, η^2_p= .050, MSE= .102
8 AS = 19; S = 16	F (1,33) = .124, p = .727, η^2_p= .004, MSE= .234	**F (6,198) = 2.46, p = .026, η^2_p= .069**, MSE= .096	F (6,198) = 1.65, p = .135, η^2_p= .048, MSE= .096
10 AS = 15; S = 15	F (1,28) = .006, p = .938, η^2_p< .001, MSE= .134	**F (8,224) = 2.04, p = .043, η^2_p= .068**, MSE= .153	F (8,224) = .975, p = .456, η^2_p= .034, MSE= .153
12 AS = 13; S = 13	F (1,24) = .017, p = .898, η^2_p= .001, MSE= .175	F (10,240) = 1.77, p = .068, η^2_p=.069, MSE= .147	F (10,240) = .324, p = .974, η^2_p= .013, MSE= .147
15 AS = 10; S = 12	F (1,20) = 2.98, p = .100, η^2_p= .130, MSE= .101	**F (13,260) = 2.14, p = .012, η^2_p= .097**, MSE= .171	F (13,260) = .760, p = .702, η^2_p= .037, MSE= .171

Note: significant main effects and interactions are presented in bold. ‘AS’ and ‘S’ stand for the number of participants contributing to the ANOVA from the AS and No AS groups respectively.

Appendix B4: Analysis from Experiment 4

Table B4. Analyses of the IFR serial position curves from Experiment 4, shown in Figures 10A and 10B (No AS and AS visual circles) and Figures 11A and 11B (No AS and AS visual words), using only data from trials starting with SP1 with FR scoring. At each list length, the free recall data were subjected to a 2 (group: AS and No AS) x *n* – 1 (serial position: SP, 2, …,*n*) mixed ANOVA. This was done separately for both the verbal and visuo-spatial group. Note that there were relatively few participants included in the analysis at longer list lengths.

List length	Main Effects		Interaction
	Articulatory suppression	Serial position	
Visuo-Spatial			
3 $N = 17$	$F(1,16) = 1.17$, $p = .296$, $\eta^2_p = .068$, $MSE = .060$	$F(1,16) = 2.12$, $p = .165$, $\eta^2_p = .117$, $MSE = .123$	**$F(1,16) = 4.51$, $p = .050$, $\eta^2_p = .220$, $MSE = .037$**
4 $N = 15$	$F(1,14) = .418$, $p = .528$, $\eta^2_p = .029$, $MSE = .213$	$F(2,28) = .741$, $p = .486$, $\eta^2_p = .050$, $MSE = .067$	$F(2,28) = .283$, $p = .756$, $\eta^2_p = .020$, $MSE = .169$
5 $N = 12$	$F(1,11) = .439$, $p = .521$, $\eta^2_p = .038$, $MSE = .103$	**$F(3,33) = 3.83$, $p = .019$, $\eta^2_p = .258$, $MSE = .155$**	$F(3,33) = 2.74$, $p = .059$, $\eta^2_p = .199$, $MSE = .134$
6 $N = 9$	$F(1,8) = 1.31$, $p = .285$, $\eta^2_p = .141$, $MSE = .147$	$F(4,32) = .205$, $p = .934$, $\eta^2_p = .025$, $MSE = .163$	$F(4,32) = 1.04$, $p = .404$, $\eta^2_p = .115$, $MSE = .190$
7 $N = 7$	$F(1,6) = .364$, $p = .569$, $\eta^2_p = .057$, $MSE = .058$	**$F(5,30) = 3.06$, $p = .024$, $\eta^2_p = .338$, $MSE = .128$**	$F(5,30) = 1.86$, $p = .132$, $\eta^2_p = .236$, $MSE = .132$
8 $N = 7$	$F(1,6) = .962$, $p = .365$, $\eta^2_p = .138$, $MSE = .156$	$F(6,36) = .196$, $p = .976$, $\eta^2_p = .032$, $MSE = .172$	$F(6,36) = .436$, $p = .850$, $\eta^2_p = .068$, $MSE = .142$
10 $N = 3$	$F(1,2) = 9.14$, $p = .094$, $\eta^2_p = .821$, $MSE = .032$	$F(8,16) = 1.93$, $p = .126$, $\eta^2_p = .490$, $MSE = .092$	$F(8,16) = 2.31$, $p = .073$, $\eta^2_p = .536$, $MSE = .142$
12 $N = 2$	$F(1,1) = 25.0$, $p = .126$, $\eta^2_p = .962$, $MSE = .023$	$F(10,10) = 1.16$, $p = .411$, $\eta^2_p = .537$, $MSE = .173$	$F(10,10) = 1.37$, $p = .314$, $\eta^2_p = .578$, $MSE = .123$
15 $N = 3$	$F(1,2) < .001$, $p = 1.00$, $\eta^2_p < .001$, $MSE = .009$	$F(13,26) = .846$, $p = .613$, $\eta^2_p = .297$, $MSE = .120$	$F(13,26) = .558$, $p = .865$, $\eta^2_p = .218$, $MSE = .172$
Verbal			
3 $N = 20$	**$F(1,19) = 27.3$, $p < .001$, $\eta^2_p = .590$, $MSE = .017$**	$F(1,19) = .024$, $p = .878$, $\eta^2_p = .001$, $MSE = .021$	$F(1,19) = .253$, $p = .621$, $\eta^2_p = .013$, $MSE = .018$
4 $N = 20$	**$F(1,19) = 35.2$, $p < .001$, $\eta^2_p = .649$, $MSE = .075$**	$F(2,38) = 1.66$, $p = .203$, $\eta^2_p = .080$, $MSE = .099$	**$F(2,38) = 4.45$, $p = .018$, $\eta^2_p = .190$, $MSE = .080$**
5 $N = 15$	**$F(1,14) = 24.4$, $p < .001$, $\eta^2_p = .635$, $MSE = .065$**	**$F(3,42) = 4.33$, $p = .009$, $\eta^2_p = .236$, $MSE = .110$**	$F(3,42) = 2.13$, $p = .111$, $\eta^2_p = .132$, $MSE = .144$
6 $N = 10$	**$F(1,9) = 15.3$, $p = .004$, $\eta^2_p = .630$, $MSE = .094$**	$F(4,36) = 1.18$, $p = .337$, $\eta^2_p = .116$, $MSE = .147$	$F(4,36) = 1.74$, $p = .163$, $\eta^2_p = .162$, $MSE = .116$
7 $N = 13$	**$F(1,12) = 8.65$, $p = .012$, $\eta^2_p = .419$, $MSE = .090$**	$F(5,60) = 2.08$, $p = .081$, $\eta^2_p = .148$, $MSE = .137$	$F(5,60) = 1.66$, $p = .158$, $\eta^2_p = .122$, $MSE = .192$

8 *N* = 7	**$F(1,6) = 8.41, p = .027, \eta^2_p = .584, MSE = .047$**	$F(6,36) = 1.79, p = .129, \eta^2_p = .230, MSE = .181$	**$F(6,36) = 3.63, p = .006, \eta^2_p = .377, MSE = .095$**
10 *N* = 7	$F(1,6) = 2.07, p = .200, \eta^2_p = .256, MSE = .056$	**$F(8,48) = 3.82, p = .002, \eta^2_p = .389, MSE = .105$**	$F(8,48) = 1.45, p = .202, \eta^2_p = .194, MSE = .123$
12 *N* = 5	$F(1,4) = 3.82, p = .122, \eta^2_p = .489, MSE = .086$	$F(10,40) = 1.90, p = .075, \eta^2_p = .322, MSE = .129$	$F(10,40) = 1.05, p = .419, \eta^2_p = .209, MSE = .134$
15 *N* = 3	$F(1,2) = 3.51, p = .202, \eta^2_p = .637, MSE = .024$	**$F(13,26) = 2.69, p = .015, \eta^2_p = .573, MSE = .076$**	**$F(13,26) = 2.35, p = .031, \eta^2_p = .540, MSE = .050$**

Note: significant main effects and interactions are presented in bold. ‘AS’ and ‘S’ stand for the number of participants contributing to the ANOVA from the AS and No AS groups respectively.

Appendix C: Analysis of Serial Position Curves when P(FR=Last4)

Appendix C1: Analysis from Experiment 1

Table C1 - Analyses of the IFR serial position curves from Experiment 1, shown in Figure 4B, using only data from trials starting with one of the last 4 serial positions using FR scoring. At each list length, the free recall data were subjected to a repeated measures ANOVA. Note that there were relatively few participants included in the analysis at shorter list lengths.

List Length	Main effect of Serial Position
3 $N = 12$	$F(2,22) = 0.788$, $p = .467$, $\eta^2_p = 0.067$, $MSE = .060$
4 $N = 15$	$F(3,42) = 2.68$, $p = .059$, $\eta^2_p = 0.161$, $MSE = .066$
5 $N = 17$	$F(4,64) = 1.73$, $p = .154$, $\eta^2_p = 0.098$, $MSE = .062$
6 $N = 17$	**$F(5,80) = 2.90$, $p = .019$, $\eta^2_p = 0.153$, $MSE = .089$**
7 $N = 16$	**$F(6,90) = 3.76$, $p = .002$, $\eta^2_p = 0.200$, $MSE = .085$**
8 $N = 18$	**$F(7,119) = 3.53$, $p = .002$, $\eta^2_p = 0.172$, $MSE = .102$**
10 $N = 16$	**$F(9,135) = 5.11$, $p < .001$, $\eta^2_p = 0.254$, $MSE = .089$**
12 $N = 17$	**$F(11,176) = 3.99$, $p < .001$, $\eta^2_p = 0.199$, $MSE = .090$**
15 $N = 15$	**$F(14,196) = 4.01$, $p < .001$, $\eta^2_p = 0.223$, $MSE = .064$**

Note: significant main effects are presented in bold

Appendix C2: Analysis from Experiment 2

Table C2 - Analyses of the IFR serial position curves from Experiment 2, shown in Figure 4E, using only data from trials starting with one of the last 4 serial positions using FR scoring. At each list length, the free recall data were subjected to a repeated measures ANOVA. Note that there were relatively few participants included in the analysis at shorter list lengths.

List Length	Main effect of Serial Position
3 $N = 14$	**$F(2,26) = 4.31$, $p = .024$, $\eta^2_p = 0.249$, $MSE = .094$**
4 $N = 15$	**$F(3,42) = 10.008$, $p < .001$, $\eta^2_p = 0.417$, $MSE = .104$**
5 $N = 20$	$F(4,76) = 1.125$, $p = .351$, $\eta^2_p = 0.056$, $MSE = .155$
6 $N = 19$	**$F(5,90) = 2.963$, $p = .016$, $\eta^2_p = 0.141$, $MSE = .160$**
7 $N = 20$	**$F(6,114) = 5.427$, $p < .001$, $\eta^2_p = 0.222$, $MSE = .107$**
8 $N = 21$	**$F(7,140) = 6.572$, $p < .001$, $\eta^2_p = 0.247$, $MSE = .123$**
10 $N = 21$	**$F(9,180) = 3.05$, $p = .002$, $\eta^2_p = 0.132$, $MSE = .129$**
12 $N = 20$	**$F(11,209) = 2.73$, $p = .003$, $\eta^2_p = 0.126$, $MSE = 0.116$**
15 $N = 19$	**$F(14,252) = 2.42$, $p = .003$, $\eta^2_p = 0.119$, $MSE = 0.148$**

Note: significant main effects are presented in bold

Appendix C3: Analysis from Experiment 3

Table C3. Analyses of the IFR serial position curves from Experiment 3, shown in Figure 9C and 9D, using only data from trials starting with one of the last 4 serial positions using FR scoring. At each list length, the free recall data were subjected to a 2 (group: AS and No AS) x $n - 1$ (serial position: SP, 2, …,n) mixed ANOVA. SP1 was excluded since it was, by definition, always recalled. Note that there were relatively few participants included in the analysis at shorter list lengths.

List length	Main Effects		Interaction
	Articulatory suppression	Serial position	
3 AS = 18; S = 17	F (1,33) = .658, p = .423, η^2_p = .020, MSE = .045	**F (2,66) = 5.42, p = .007, η^2_p= .134, MSE = .041**	F (2,66) = 1.13, p = .330, η^2_p= .033, MSE = .041
4 AS = 17; S = 17	F (1,32) = 1.66, p = .207, η^2_p= .049, MSE = .040	F (3,96) = 1.58, p = .200, η^2_p= .040, MSE = .034	F (3,96) = .221, p = .882, η^2_p= .007, MSE = .034
5 AS = 18; S = 17	F (1,33) = .316, p = .578, η^2_p= .009, MSE = .109	**F (4,132) = 4.59, p = .002, η^2_p= .109, MSE = .058**	F (4,132) = 1.66, p = .163, η^2_p= .048, MSE = .058
6 AS = 17; S = 18	F (1,33) = 2.39, p = .132, η^2_p= .067, MSE = .150	**F (5,165) = 6.21, p < .001, η^2_p= .163, MSE = .069**	F (5,165) = .428, p = .828, η^2_p= .013, MSE = .069
7 AS = 17; S = 18	F (1,33) = .552, p = .463, η^2_p= .016, MSE = .124	**F (6,198) = 9.54, p < .001, η^2_p= .211, MSE = .066**	F (6,198) = .626, p = .709, η^2_p= .019, MSE = .066
8 AS = 17; S = 18	**F (1,33) = 4.57, p = .040, η^2_p**= .122, MSE = .098	**F (7,231) = 12.7, p < .001, η^2_p= .278, MSE = .064**	F (7,231) = .674, p = .694, η^2_p= .020, MSE = .064
10 AS = 17; S = 19	F (1,34) = 1.40, p = .245, η^2_p = .040, MSE = .069	**F (9,306) = 7.68, p < .001, η^2_p= .184, MSE = .073**	F (9,306) = .354, p =.956, η^2_p= .010, MSE = .073
12 AS = 18; S = 20	F (1,36) = .198, p = .659, η^2_p= .005, MSE = .073	**F (11,396) = 7.93, p < .001, η^2_p=.180, MSE = .084**	F (11,396) = 1.78, p = .056, η^2_p=.047, MSE = .084
15 AS = 19; S = 19	F (1,36) = 1.53, p = .224, η^2_p= .041, MSE = .091	**F (14,504) = 6.31, p < .001, η^2_p= .141, MSE = .078**	F (14,504) = 1.66, p = .060, η^2_p= .044, MSE = .078

Note: significant main effects and interactions are presented in bold. 'AS' and 'S' stand for the number of participants contributing to the ANOVA from the AS and No AS groups respectively.

Appendix C4: Analysis from Experiment 4

Table C4. Analyses of the IFR serial position curves from Experiment 4, shown in Figures 10C and 10D (No AS and AS Visuo-spatial conditions) and Figures 11C and 11D (No AS and AS Verbal conditions), using only data from trials starting with one of the last 4 serial positions using FR scoring. At each list length, the free recall data were subjected to a 2 (group: AS and No AS) x $n-1$ (serial position: SP, 2, …,n) mixed ANOVA. This was done separately for both the verbal and visuo-spatial group.. Note that there were relatively few participants included in the analysis at shorter list lengths.

List length	Main Effects		Interaction
	Articulatory suppression	Serial position	
Visuo-Spatial			
3 $N = 4$	$F(1,3) = .086$, $p = .798$, $\eta^2_p = .028$, $MSE = .122$	**$F(2,6) = 9.38$, $p = .014$, $\eta^2_p = .758$, $MSE = .092$**	$F(2,6) = .326$, $p = .734$, $\eta^2_p = .098$, $MSE = .130$
4 $N = 8$	**$F(1,7) = 6.60$, $p = .037$, $\eta^2_p = .485$, $MSE = .052$**	**$F(3,21) = 5.50$, $p = .014$, $\eta^2_p = .391$, $MSE = .214$**	$F(3,21) = .311$, $p = .817$, $\eta^2_p = .043$, $MSE = .127$
5 $N = 9$	$F(1,8) = 1.97$, $p = .198$, $\eta^2_p = .198$, $MSE = .160$	**$F(4,32) = 8.00$, $p < .001$, $\eta^2_p = .500$, $MSE = .127$**	$F(4,32) = 2.62$, $p = .054$, $\eta^2_p = .246$, $MSE = .140$
6 $N = 9$	$F(1,8) = .327$, $p = .583$, $\eta^2_p = .039$, $MSE = .106$	**$F(5,40) = 17.8$, $p < .001$, $\eta^2_p = .689$, $MSE = .087$**	$F(5,40) = .220$, $p = .952$, $\eta^2_p = .027$, $MSE = .094$
7 $N = 10$	**$F(1,9) = 6.25$, $p = .034$, $\eta^2_p = .410$, $MSE = .039$**	**$F(6,54) = 4.33$, $p = .001$, $\eta^2_p = .325$, $MSE = .140$**	$F(6,54) = .636$, $p = .701$, $\eta^2_p = .066$, $MSE = .161$
8 $N = 10$	$F(1,9) = 1.75$, $p = .219$, $\eta^2_p = .162$, $MSE = .074$	**$F(7,63) = 16.7$, $p < .001$, $\eta^2_p = .650$, $MSE = .084$**	$F(7,63) = .377$, $p = .913$, $\eta^2_p = .040$, $MSE = .098$
10 $N = 13$	$F(1,12) = .866$, $p = .371$, $\eta^2_p = .067$, $MSE = .074$	**$F(9,108) = 14.9$, $p < .001$, $\eta^2_p = .554$, $MSE = .098$**	$F(9,108) = .869$, $p = .555$, $\eta^2_p = .068$, $MSE = .107$
12 $N = 10$	$F(1,9) = 2.18$, $p = .174$, $\eta^2_p = .195$, $MSE = .077$	**$F(11,99) = 12.4$, $p < .001$, $\eta^2_p = .579$, $MSE = .075$**	$F(11,99) = 1.64$, $p = .100$, $\eta^2_p = .154$, $MSE = .048$
15 $N = 14$	**$F(1,13) = 7.57$, $p = .016$, $\eta^2_p = .368$, $MSE = .048$**	**$F(14,182) = 9.72$, $p < .001$, $\eta^2_p = .428$, $MSE = .096$**	$F(14,182) = 1.05$, $p = .405$, $\eta^2_p = .075$, $MSE = .086$
Verbal			
3 $N = 2$	$F(1,2) = 1.00$, $p = .500$, $\eta^2_p = .500$, $MSE = .083$	$F(1,2) = 1.00$, $p = .500$, $\eta^2_p = .500$, $MSE = .083$	$F(1,2) = 1.00$, $p = .500$, $\eta^2_p = .500$, $MSE = .083$
4 $N = 7$	$F(1,6) = 3.74$, $p = .101$, $\eta^2_p = .384$, $MSE = .144$	$F(3,18) = 1.35$, $p = .290$, $\eta^2_p = .184$, $MSE = .165$	**$F(3,18) = 3.69$, $p = .031$, $\eta^2_p = .381$, $MSE = .165$**
5 $N = 11$	**$F(1,10) = 9.77$, $p = .011$, $\eta^2_p = .494$, $MSE = .164$**	**$F(4,40) = 3.8$, $p = .009$, $\eta^2_p = .279$, $MSE = .079$**	**$F(4,40) = 3.38$, $p = .018$, $\eta^2_p = .253$, $MSE = .069$**
6 $N = 15$	**$F(1,14) = 25.1$, $p < .001$, $\eta^2_p = .632$, $MSE = .067$**	**$F(5,70) = 15.8$, $p < .001$, $\eta^2_p = .530$, $MSE = .084$**	**$F(5,70) = 3.80$, $p = .004$, $\eta^2_p = .213$, $MSE = .063$**
7 $N = 14$	**$F(1,13) = 18.7$, $p < .001$, $\eta^2_p = .590$, $MSE = .054$**	**$F(6,78) = 18.4$, $p < .001$, $\eta^2_p = .585$, $MSE = .068$**	**$F(6,78) = 2.77$, $p = .017$, $\eta^2_p = .176$, $MSE = .098$**

8 N = 16	**F(1,15) = 34.7, p < .001, η^2_p= .698, MSE=.039**	**F(7,105) = 14.2, p < .001, η^2_p= .486, MSE=.091**	F(7,105) = 1.24, p = .286, η^2_p= .076, MSE=.101
10 N = 15	**F(1,14) = 21.7, p < .001, η^2_p=.608, MSE= .038**	**F(9,126) = 23.1, p < .001, η^2_p=.622, MSE= .069**	F(9,126) = .709, p = .700, η^2_p=.048, MSE= .078
12 N = 16	**F(1,15) = 37.8, p < .001, η^2_p= .716, MSE=.034**	**F(11,165) = 20.0, p < .001, η^2_p= .571, MSE=.074**	**F(11,165) = 2.04, p = .028, η^2_p= .119, MSE=.060**
15 N = 18	**F(1,17) = 17.8, p < .001, η^2_p= .512, MSE=.073**	**F(14,238) = 23.3, p < .001, η^2_p= .578, MSE=.065**	**F(14,238) = 2.26, p = .007, η^2_p= .117, MSE=.053**

Note: significant main effects and interactions are presented in bold. ‘AS’ and ‘S’ stand for the number of participants contributing to the ANOVA from the AS and No AS groups respectively.

Appendix D: Analysis of Serial Position Curves when P(FR=SP1) using SR scoring.

Appendix D1: Analysis from Experiment 1

Table D1- Analyses of the IFR serial position curves from Experiment 1, shown in Figure 4C, using only data from trials starting with SP1 using SR scoring. At each list length, the free recall data were subjected to a repeated measures ANOVA. Note that there were relatively few participants included in the analysis at longer list lengths.

List Length	Main effect of Serial Position
3 $N = 20$	$F(1,19) = 3.58$, $p = .074$, $\eta^2_p = 0.158$, $MSE = .017$
4 $N = 20$	$F(2,38) = 2.16$, $p = .129$, $\eta^2_p = 0.102$, $MSE = .033$
5 $N = 20$	**$F(3,57) = 3.88$, $p = .014$, $\eta^2_p = 0.107$, $MSE = .053$**
6 $N = 18$	**$F(4,68) = 6.49$, $p < .001$, $\eta^2_p = 0.276$, $MSE = .061$**
7 $N = 16$	**$F(5,75) = 7.50$, $p < .001$, $\eta^2_p = 0.333$, $MSE = .032$**
8 $N = 16$	**$F(6,90) = 2.80$, $p = .015$, $\eta^2_p = 0.157$, $MSE = .063$**
10 $N = 15$	$F(8,112) = 1.91$, $p = .065$, $\eta^2_p = 0.120$, $MSE = .039$
12 $N = 11$	**$F(10,100) = 3.46$, $p = .001$, $\eta^2_p = 0.257$, $MSE = .020$**
15 $N = 11$	**$F(13,130) = 3.34$, $p < .001$, $\eta^2_p = 0.250$, $MSE = .029$**

Note: significant main effects are presented in bold

Appendix D2: Analysis from Experiment 2

Table D2- Analyses of the IFR serial position curves from Experiment 2, shown in Figure 4F, using only data from trials starting with SP1 using SR scoring. At each list length, the free recall data were subjected to a repeated measures ANOVA. Note that there were relatively few participants included in the analysis at longer list lengths.

List Length	Main effect of Serial Position
3 $N = 18$	$F(1,17) = 0.121$, $p = .733$, $\eta^2_p = 0.007$, $MSE = .058$
4 $N = 18$	$F(2,34) = 0.209$, $p = .812$, $\eta^2_p = 0.012$, $MSE = .096$
5 $N = 14$	**$F(3,39) = 6.08$, $p = .002$, $\eta^2_p = 0.319$, $MSE = .111$**
6 $N = 12$	$F(4,44) = 1.74$, $p = .158$, $\eta^2_p = 0.137$, $MSE = .133$
7 $N = 11$	$F(5,50) = 1.24$, $p = .306$, $\eta^2_p = 0.110$, $MSE = .042$
8 $N = 8$	$F(6,42) = 1.49$, $p = .207$, $\eta^2_p = 0.175$, $MSE = .112$
10 $N = 7$	$F(8,48) = 1.70$, $p = .124$, $\eta^2_p = 0.220$, $MSE = .063$
12 $N = 7$	$F(10,60) = 1.84$, $p = .073$ $\eta^2_p = 0.235$, $MSE = .032$
15 $N = 3$	$F(13,26) = 0.652$, $p = .788$, $\eta^2_p = 0.246$, $MSE = .126$

Note: significant main effects are presented in bold

Appendix D3: Analysis from Experiment 3

Table D3. Analyses of the IFR serial position curves from Experiment 3, shown in Figures 9E and 9F, using only data from trials starting with SP1 with SR scoring. At each list length, the free recall data were subjected to a 2 (group: AS and No AS) x n – 1 (serial position: SP, 2, …,n) mixed ANOVA. Note that there were relatively few participants included in the analysis at longer list lengths.

List length	Main Effects		Interaction
	Articulatory suppression	Serial position	
3 AS = 20; S = 19	F (1,37)=.830, p = .368, η^2_p= .022, MSE= .119	**F (1,37) = 5.24, p = .028, η^2_p= .124, MSE= .009**	F (1,37) = .591, p = .447, η^2_p = .016, MSE= .009
4 AS = 20; S = 20	F (1,38) =.237, p = .629, η^2_p= .006, MSE= .199	F (2,76) = 1.10, p = .337, η^2_p= .028, MSE= .052	F (2,76) = .057, p = .944, η^2_p = .002, MSE= .052
5 AS = 18; S = 19	F (1,35) = 3.83, p = .058, η^2_p= .099, MSE= .126	**F (3,105) = 4.54, p = .005, η^2_p= .115, MSE= .054**	F (3,105) = .519, p = .670, η^2_p = .015, MSE= .054
6 AS = 17; S = 20	F (1,35) = 1.60, p = .214, η^2_p= .044, MSE= .110	**F (4,140) = 9.38, p < .001, η^2_p= .211, MSE= .063**	F (4,140) = .437, p = .782, η^2_p = .012, MSE= .063
7 AS = 17; S = 18	F (1,33) = .449, p = .507, η^2_p= .013, MSE= .106	**F (5,165) = 5.14, p < .001, η^2_p= .135, MSE= .067**	F (5,165) = 1.80, p = .117, η^2_p = .052, MSE= .067
8 AS = 19; S = 16	F (1,33) = .238, p = .629, η^2_p= .007, MSE= .067	**F (6,198) = 9.04, p < .001, η^2_p= .215, MSE= .041**	F (6,198) = .562, p = .760, η^2_p = .017, MSE= .041
10 AS = 15; S = 15	F (1,28) = .635, p = .432, η^2_p=.022, MSE= .119	**F (8,224) = 4.45, p < .001, η^2_p= .137, MSE= .045**	F (8,224) = 1.13, p = .344, η^2_p = .039, MSE= .045
12 AS = 13; S = 13	F (1,24) = .087, p = .721, η^2_p= .004, MSE= .047	F (10,240) = 1.80, p = .061, η^2_p=.070, MSE= .041	F (10,240) = .915, p = .520, η^2_p = .037, MSE= .041
15 AS = 10; S = 12	F (1,20) = .239, p = .239, η^2_p= .068, MSE= .044	**F (13,260) = 4.38, p < .001, η^2_p= .180, MSE= .131**	F (13,260) = .569, p = .878, η^2_p = .028, MSE= .031

Note: significant main effects and interactions are presented in bold. ‘AS’ and ‘S’ stand for the number of participants contributing to the ANOVA from the AS and No AS groups respectively.

Appendix D4: Analysis from Experiment 4

Table D4. Analyses of the IFR serial position curves from Experiment 4, shown in Figures 10E and 10F (No AS and AS Visuo-spatial conditions) and Figures 11E and 11F (No AS and AS Verbal conditions), using only data from trials starting with serial position 1 using serial recall scoring. At each list length, the data were subjected to a 2 (group: AS and No AS) x *n* – 1 (serial position: SP, 2, …,*n*) mixed ANOVA. This was done separately for both the verbal and visuo-spatial group. Note that there were relatively few participants included in the analysis at longer list lengths.

List length	Main Effects		Interaction
	Articulatory suppression	Serial position	
Visuo-Spatial			
3 *N* = 17	$F(1,16) = .618, p = .443, \eta^2_p = .037, MSE = .067$	$F(1,16) = 2.60, p = .126, \eta^2_p = .140, MSE = .117$	**$F(1,16) = 4.94, p = .041, \eta^2_p = .236, MSE = .038$**
4 *N* = 15	$F(1,14) = .273, p = .610, \eta^2_p = .019, MSE = .238$	$F(2,28) = .141, p = .869, \eta^2_p = .010, MSE = .041$	$F(2,28) = .348, p = .709, \eta^2_p = .024, MSE = .128$
5 *N* = 12	$F(1,11) = .001, p = .978, \eta^2_p < .001, MSE = .095$	**$F(3,33) = 3.30, p = .032, \eta^2_p = .230, MSE = .142$**	$F(3,33) = 2.11, p = .118, \eta^2_p = .161, MSE = .101$
6 *N* = 9	$F(1,8) = 3.45, p = .100, \eta^2_p = .301, MSE = .181$	$F(4,32) = .648, p = .632, \eta^2_p = .075, MSE = .075$	$F(4,32) = .231, p = .919, \eta^2_p = .028, MSE = .090$
7 *N* = 7	$F(1,6) = .478, p = .515, \eta^2_p = .074, MSE = .044$	$F(5,30) = 2.19, p = .082, \eta^2_p = .267, MSE = .024$	$F(5,30) = 1.60, p = .191, \eta^2_p = .210, MSE = .022$
8 *N* = 7	$F(1,6) = .075, p = .793, \eta^2_p = .012, MSE = .060$	$F(6,36) = 2.27, p = .058, \eta^2_p = .275, MSE = .047$	$F(6,36) = .522, p = .788, \eta^2_p = .080, MSE = .030$
10 *N* = 3	$F(1,2) = 1.23, p = .383, \eta^2_p = .381, MSE = .060$	$F(8,16) = 1.68, p = .179, \eta^2_p = .457, MSE = .058$	$F(8,16) = .187, p = .989, \eta^2_p = .086, MSE = .117$
12 *N* = 2	$F(1,1) = 9.00, p = .205, \eta^2_p = .900, MSE = .006$	$F(10,10) = 2.19, p = .117, \eta^2_p = .686, MSE = .031$	$F(10,10) = .324, p = .955, \eta^2_p = .245, MSE = .081$
15 *N* = 3	$F(1,2) = 1.00, p = .423, \eta^2_p = .333, MSE = .003$	$F(13,26) = 1.00, p = .479, \eta^2_p = .333, MSE = .003$	$F(13,26) = 1.00, p = .479, \eta^2_p = .333, MSE = .003$
Verbal			
3 *N* = 20	**$F(1,19) = 39.5, p < .001, \eta^2_p = .675, MSE = .059$**	**$F(1,19) = 22.7, p < .001, \eta^2_p = .544, MSE = .006$**	**$F(1,19) = 17.9, p < .001, \eta^2_p = .485, MSE = .0004$**
4 *N* = 20	**$F(1,19) = 75.0, p < .001, \eta^2_p = .798, MSE = .089$**	**$F(2,38) = 32.0, p < .001, \eta^2_p = .628, MSE = .042$**	**$F(2,38) = 3.74, p = .033, \eta^2_p = .164, MSE = .057$**
5 *N* = 15	**$F(1,14) = 19.6, p = .001, \eta^2_p = .584, MSE = .169$**	**$F(3,42) = 22.9, p < .001, \eta^2_p = .621, MSE = .061$**	$F(3,42) = 1.45, p = .242, \eta^2_p = .094, MSE = .052$
6 *N* = 10	**$F(1,9) = 6.04, p = .036, \eta^2_p = .401, MSE = .219$**	**$F(4,36) = 15.5, p < .001, \eta^2_p = .632, MSE = .040$**	**$F(4,36) = 4.29, p = .006, \eta^2_p = .323, MSE = .050$**

7 $N = 13$	$F(1,12) = 4.37$, $p = .059$, $\eta^2_p = .267$, $MSE = .142$	**$F(5,60) = 20.6$, $p < .001$, $\eta^2_p = .632$, $MSE = .044$**	$F(5,60) = 2.07$, $p = .082$, $\eta^2_p = .147$, $MSE = .074$
8 $N = 7$	**$F(1,6) = 10.7$, $p = .017$, $\eta^2_p = .641$, $MSE = .086$**	**$F(6,36) = 14.7$, $p < .001$, $\eta^2_p = .710$, $MSE = .062$**	**$F(6,36) = 2.62$, $p = .033$, $\eta^2_p = .304$, $MSE = .053$**
10 $N = 7$	**$F(1,6) = 17.9$, $p = .006$, $\eta^2_p = .749$, $MSE = .036$**	**$F(8,48) = 8.71$, $p < .001$, $\eta^2_p = .592$, $MSE = .038$**	**$F(8,48) = 4.74$, $p < .001$, $\eta^2_p = .441$, $MSE = .025$**
12 $N = 5$	**$F(1,4) = 11.9$, $p = .026$, $\eta^2_p = .748$, $MSE = .048$**	**$F(10,40) = 4.98$, $p < .001$, $\eta^2_p = .555$, $MSE = .044$**	**$F(10,40) = 2.53$, $p = .018$, $\eta^2_p = .387$, $MSE = .041$**
15 $N = 3$	**$F(1,2) = 112$, $p = .009$, $\eta^2_p = .983$, $MSE = .003$**	**$F(13,26) = 8.81$, $p < .001$, $\eta^2_p = .815$, $MSE = .029$**	**$F(13,26) = 12.2$, $p < .001$, $\eta^2_p = .859$, $MSE = .007$**

Note: significant main effects and interactions are presented in bold. 'AS' and 'S' stand for the number of participants contributing to the ANOVA from the AS and No AS groups respectively.