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Exploring the retrieval dynamics of delayed and final free recall: Further evidence for temporal-contextual search ☆

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ABSTRACT

Retrieval dynamics in free recall were explored based on a two-stage search model that relies on temporal-contextual cues. Participants were tested on both delayed and final free recall and correct recalls, errors, and latency measures were examined. In delayed free recall participants began recall with the first word presented and tended to recall items in a forward manner leading to large primacy and small recency effects. In final free recall participants tended to begin recall with a word from the last list presented and the first word in that list. Participants tended to cluster words based on list membership and the results for within list clusters were very similar to the delayed free recall results. Furthermore, participants tended to cluster items based on the output position from the initial delayed free recall test. When switching to a new list of items, participants tended to switch to lists presented in close temporal proximity to the current list and then recall the first word in the new list similar to delayed free recall. Overall the results are consistent with a two-stage search model in which temporal-contextual cues are used to retrieve items.

Single trial free recall, in which a list of items is presented to participants and they are required to recall the items in any order they wish, has long interested memory researchers and played a prominent role in theories of memory (Crowder, 1976; Murdock, 1974; Tulving, 1968). In this task participants are typically presented with a list of random words, yet recall is rarely random. Rather a number of systematic effects are apparent after close examination of the data. Perhaps the most well known are serial position effects in which items presented at the beginning (primacy) and end (recency) of the list tend to be remembered better than items presented in the middle of the list (Murdock, 1962). Additionally, these effects tend to change as a function of a number of variables including the presence of a distractor task after the last presented item (delayed free recall; Glanzer & Cunitz, 1966), word frequency (Raymond, 1969), presentation rate (Glanzer & Cunitz, 1966), list-length (Murdock, 1962), and proactive interference (Craik & Birtwistle, 1971). Other systematic effects include the finding that participants typically begin recall with either the last word presented or the first word presented (i.e., probability of first recall; Howard & Kahana, 1999), the finding that items presented close together in time tend to be recalled close together (i.e., lag recency; Kahana, 1996), and the finding that items with semantic associations tend to be recalled close together (Howard & Kahana, 2002a).

Furthermore, when participants make errors, these errors tend to be items that were presented on a previous list (previous list intrusions) or items that were never presented but are semantically or phonologically associated with one of the target items (Craik, 1968). Thus, despite the fact that lists in a typical free recall study are usually composed of unrelated random words, these items tend to be recalled in a somewhat systematic fashion. The cur-

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rent study examined retrieval dynamics in delayed and final free recall to better understand these systematic effects and their implications for how individuals recall information from the recent past.

Temporal context in free recall

It has long been recognized that context in some form plays an important role in our ability to remember information from our past. Indeed, in his classic attack on the notion of decay as a primary cause of forgetting, McGeoch (1932) suggested three factors were important for forgetting: competition between representations, fluctuations of context in which the retrieval context no longer matched the encoding context, and inadequate mental set at the time of testing. The notion that changes in context between encoding and retrieval conditions can cause forgetting has since been a major component of many theories of memory (e.g., Anderson & Bower, 1972; Bower, 1972; Brown, Neath, & Chater, 2007; Brown, Preece, & Hulme, 2000; Capaldi & Neath, 1995; Glenberg, Bradley, Stevenson, Kraus, & Renzaglia, 1983; Howard & Kahana, 1999; Mensink & Raaijmakers, 1988; Raaijmakers & Shiffrin, 1980; Tulving & Thomson, 1973). Much of this work relies on Tulving's (1983) notion of episodic memory in which information is associated with the particular spatio-temporal context in which it is presented allowing for retrieval of both content and context information. For instance, in a typical free recall task the items presented on each list are associated with the particular spatio-temporal context in which they are presented (i.e., a running room in the Psychology building on a Thursday afternoon in November). When asked to recall, participants rely on this contextual information to generate items that were presented in this given context. Although theories differ in the underlying mechanisms, these views suggest that at presentation of each item, the item's content information is bound with the current context creating an episodic representation. At recall, attempts are made to reinstate the context in order to generate the correct episodic representations. Accurate recall then, will depend on the ability to correctly reinstate the learning context at test.

A number of theories have suggested that different contextual elements from a hierarchy are associated with items at encoding. Importantly, in these views it is suggested that these different contextual elements change at different rates with elements higher up in the hierarchy changing slowly and elements lower in the hierarchy changing rapidly (e.g., Brown et al., 2000; Estes, 1955; Glenberg et al., 1980, 1983; Lee & Estes, 1981; Unsworth & Engle, 2007). At the highest level of the hierarchy are global contextual elements which are associated with features/attributes that change little during the course of the experiment including the room the experiment is in, who the experimenter is, and the general time of day. At the next level of the hierarchy it is assumed that there are contextual elements that are broadly associated with each list. Finally, at the lowest level of the hierarchy are rapidly changing contextual elements associated with each to-be-remembered (TBR) item. At encoding it is assumed that contextual elements from each level of the hierarchy are associated with each TBR item. At recall temporal-contextual cues composed of these contextual elements are used to focus the search set from which items are sampled from. As suggested above, the effectiveness of these cues will depend on the ability to reinstate the encoding context at retrieval (i.e., encoding specificity, Tulving & Thomson, 1973). Importantly, cues composed of contextual elements from the lower levels in the hierarchy will focus the search to a greater extent than cues composed of contextual elements for higher levels in the hierarchy leading to a higher probability of retrieving correct representations (i.e., cue-overload, Watkins, 1979).

A number of pieces of evidence are consistent with this general framework. For instance, a great deal of work has suggested that long-term recency effects found in the continuous distractor paradigm are due to contextual retrieval processes whereby items presented close to the recall period (recency items) are more temporally distinct than items further away from the recall period (midlist items; Glenberg et al., 1980; Howard & Kahana, 1999; Neath, 1993). In temporal-contextual retrieval theories of long-term recency it is assumed that at retrieval recency items share many contextual elements with the testing context leading to a relatively constrained search for recency items. Midlist items share less contextual elements with the testing context leading to a less constrained search and a lower probability of recall for these items (e.g., Glenberg et al., 1983). Thus, the recency effect in the continuous distractor task is seen as a direct consequence of temporal-contextual retrieval processes.

Additional evidence in favor of temporal-contextual retrieval processes is the lag-recency effect observed by Kahana and colleagues (Howard & Kahana, 1999; Kahana, 1996). As noted previously, the lag-recency (or contiguity effect) refers to the finding that items presented in close temporal proximity (and hence share many contextual elements) tend to be recalled in close proximity. That is, if a participant recalls a word from input serial position 5 they are more likely to recall a word presented in input serial position 6 next than a word presented in input serial position 10. Furthermore, Kahana and colleagues have found a distinct asymmetry in lag-recency effects whereby the effect is stronger in the forward direction (recall of item 5 and then item 6) than in the backward direction (recall of item 6 then item 5). Lag-recency effects have been found in multiple free recall tasks including immediate, delayed, and continuous distractor free recall. Howard and Kahana (1999, 2002b) have suggested that these effects are indicative of a contextual retrieval process where items sampled based on the context present at test as well as context associated with the just recalled items. Thus, once item 5 is recalled its context is used to search and retrieve subsequent items. Items that share contextual elements with the just recalled item (i.e., item 6) will then have a higher probability of being sampled than items that share few contextual elements with the just recalled item (i.e., item 10). Like long-term recency effects, lag-recency effects suggest that temporal context is important in free recall tasks.

A similar argument in favor of the importance of temporal context in free recall comes from studies of the build-up and release of proactive interference (PI). In temporal discrimination theories of PI it is assumed that PI accrues because participants are unable to focus their search on only the most recently presented items, and instead search through most or all of the recently presented items (e.g., Baddeley, 1990; Bennett, 1975; Brown et al., 2007; Crowder, 1976; Wixted & Rohrer, 1993). For instance, on List 1 of a free recall task participants can use a cue to search memory such as "retrieve all recently presented words." Representations that were recently presented are then activated and recalled. On List 2 this same cue will not only activate all items that are associated with List 2, but also many items associated with List 1 due to fact that the lists will share many contextual elements. Thus, this will increase the likelihood that a previous list intrusion is recalled, and reduce the overall likelihood that a correct item is recalled. Evidence consistent with the temporal discrimination view comes from studies that have shown that as the inter-trial interval is increased PI is drastically reduced and release effects are obtained (e.g., Kincaid & Wickens, 1970; Loess & Waugh, 1967). That is, as the number of contextual elements that are shared across lists decreases, so does the amount of PI. Likewise analyses of errors in free recall tasks have shown that when participants recall intrusions from previous lists (PLIs) these intrusions primarily come from the immediate preceding list (Murdock, 1974; Unsworth & Engle, 2007; Zaromb et al., 2006).

Finally, a number of formal models which assume that temporal-contextual retrieval and temporal discrimination are important components of free recall performance have been shown to successfully account for much of the data (e.g., Bennett, 1975; Brown et al., 2007; Howard & Kahana, 1999, 2002; Mensink & Raaijmakers, 1988; Raaijmakers & Shiffrin, 1980). Thus, in free recall tasks where typically unrelated items are presented together and recall is later required, it seems that temporal-contextual cues play an important role in the retrieval process. In the absence of other potent cues (such as semantic relatedness) individuals will rely on temporal context cues to probe their memories leading to systematic temporal effects.

Component processes involved in retrieval and a two-stage search framework

In addition to recognizing the importance of temporal context in retrieval processes, a number of theorists have suggested that retrieval is not single process, but rather there are a number of important components that aid in successful retrieval (e.g., Burgess and Shallice; 1996; Moscovitch, 1992, 1994; Norman & Bobrow, 1979; Raaijmakers & Shiffrin, 1980; Shiffrin, 1970; Williams & Hollan, 1981). In these views it is suggested that the process of retrieval first begins with the development of a retrieval plan/strategy based on the overall question that is being asked. This may include questions/requests such as "What did you do for your Birthday two years ago?," "Name as many exemplars of the category animals as you can in 1 min," or "What were the words presented on the last list ?" Such questions/statements will dictate how one decides to search their memory and what cues will be best for generating the desired information as well as how long to continue searching for the desired information. Next, it is assumed that based on the retrieval plan, the appropriate cues are specified to begin the search process and items are subsequently sampled and recovered (Raaijmakers & Shiffrin, 1980; Shiffrin, 1970) based on the match between the information specified in the retrieval cues and the information stored in the representations. After items have been recovered, they are subjected to a monitoring process which determines whether the generated information is consistent with the retrieval question and plan, and if so the items are outputted. If the items do not match the retrieval question and plan, or if there is a great deal of uncertainty (or felt rightness, Moscovitch & Winocur, 2002) associated with the information, then the items are not output and the search process starts again to retrieve more accurate information. Thus, according to these views retrieval requires a number of important component processes in order to generate the desired information. Furthermore, in these views the search for the desired information typically involves a cyclical search process in which the generated information is used as an additional cue to probe the memory system (e.g., Raaijmakers & Shiffrin, 1980; Williams & Hollan, 1981). For instance, in the Search of Associative Memory model (SAM; Raaijmakers & Shiffrin, 1980) it is assumed that the search process first relies on context information present at the time of retrieval to probe the memory system. Information (i.e., a target item) generated by the search process is then combined with the overall context information to search for the next item. Thus, the search process begins with an overarching general cue and then proceeds by utilizing information generated by this cue to further cue the memory system.

This notion of first using a general cue to generate information and then using the products of the search to further specify the search process is an integral component of search models not only for episodic memory tasks, but also for autobiographical and semantic memory tasks. For instance, Williams and Hollan (1981) suggested that when searching autobiographical memory, individuals will begin by establishing a general context cue (high school classmates) and then use the information generated by that cue (individuals who took History with you) to generate more information. Likewise a number of theories of verbal fluency have suggested a similar process involved when retrieving exemplars from a given category (e.g., animals). Here it is assumed that individuals first sample a subcategory (e.g., pets) and then sample items from the subcategory (dog, cat, fish, etc.; Gruenewald & Lockhead, 1980; Herrmann & Pearle, 1981; Wixted & Rohrer, 1994). After each exemplar is sampled, that information is used as a cue to help generate the next item and so on. Note that in these views, it is further assumed that if information from the current item does not generate any more useful information, then the current item is discarded as a cue and the search process reverts back to the general cue. Thus, it assumed that retrieving information from both autobiographical and semantic memory relies on a two-stage search process in which at the first stage a general cue is used to sample information for more specific cues and then at the second stage the more specific cues are used to sample target items. These retrieved items in turn are used to continue the search process at a fairly constrained level until no new information is retrieved, in which case the general cue is used again to sample a new set of cues. This two-stage search framework has been successfully able to account for semantic clusters in category fluency tasks and correctly predicts that time within a cluster should be shorter than time between clusters (Herrmann & Pearle, 1981; Wixted & Rohrer, 1994).

The aim of the present investigation was to utilize a similar two-stage search framework to account for systematic effects seen in episodic free recall tasks. Specifically, in order to examine delayed and final free recall performance an extension of Rundus's (1973) hierarchical retrieval model was used. In this model it is assumed that cues are first sampled based on their associative strength to the current list (based on a ratio rule), and then items are sampled from the current cue based on their associative strength to the cue. In this case, instead of searching based on semantic cues and generating clusters and items within clusters, it is assumed that individuals will search based on temporal-contextual cues as discussed previously. That is, a combination of the notion of hierarchical temporal context cues discussed previously and a two-stage search framework should be able to account for many systematic effects seen in free recall. As such this combination of a two-stage search (or multi-stage search) and hierarchical temporal context cues provides a descriptive framework with which to understand the retrieval dynamics of free recall. A schematic of the hierarchical search process is shown in Fig. 1. Here it is assumed that individuals will first sample lists based on the associative strength between the list cue and the global context. Then items within the lists will be sampled based on the associative strength between the item and the list cue. After an item (or a list) has been sampled and recalled (or recognized as an error and not recalled) it remains in the search set (sampling with replacement) and information from that item is then used along with current context cue (global or list) to generate the next item and so on.

On delayed free recall it is assumed that individuals first sample a list based on the associative strength between the global temporal context at the time of test and the temporal context associated with each list. Thus, the last list presented should have highest strength and should be sampled first. Next, items within the list will be sampled based on their strength to the list cue and the search within a list will begin with the item with strongest link with the overall list cue. Subsequent items will be generated based on the retrieved context from the previous item as well as the overall list context leading to a lag-recency effect (Howard & Kahana, 1999). The notion that items within a list are sampled based on the overall list context and retrieved item information is a basic component of many episodic search models and has been able to successfully account for a number of systematic effects in free recall including serial position effects, lag-recency effects, probability of first recall, as well as patterns of errors (Howard & Kahana, 1999; Raaijmakers & Shiffrin, 1980; Sirotin, Kimball, & Kahana, 2005). Additionally, similar search schemes have also been used to examine cumulative recall functions and inter-response times (IRTs) in delayed free recall and can account for the form of these functions (Rohrer & Wixted, 1994).

On final free recall, the search process is a little more complex. Final free recall is a task where after being presented with and recalling several previous free recall lists, participants are given a surprise recall tests for all the words presented in the experiment. Like delayed free recall it is assumed that first a list is sampled (most likely based on recency information) and then items within a list are sampled. Like category fluency tasks, it is assumed that participants will generate clusters of items, but the clusters will be based on temporal-contextual associations rather than semantic associations. Thus, search within a list in final free recall should result in fairly similar results as delayed free recall in terms of serial position effects, lag-recency effects, and probability of first recall. Furthermore, consistent with semantic fluency results, IRTs within a cluster should be fairly rapid and shorter than between cluster IRTs. This is because if no more items can be retrieved from a given temporal cluster, the search will revert back up to the global context cue and a new list will be sampled and then items within the new list will be sampled. Like search within a cluster, it is assumed that lists after the first sampled list will be sampled based on the global context plus the retrieved list context cue. This suggests that there should be lag-recency effect for lists, where nearby lists should be recalled in close proximity. Once a new list is sampled the search process starts over again at the item level. In order to examine this framework, participants were tested on 10 lists of delayed free recall and then were tested on a surprise final free recall test.

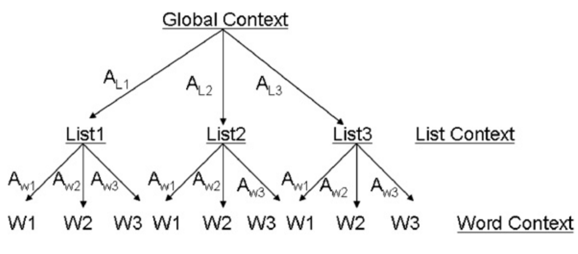

Fig. 1. Depiction of the hierarchical search scheme. Lists are sampled based on the associative strength of the List Context to the Global context (A_{Li}) and words sampled from lists based on the associative strength of the Word Context to the List Context (A_{wi}).

Method

Participants and design

Participants were 32 undergraduate students recruited from the subject-pool at the University of Georgia. Participants were between the ages of 18 and 35 and received course credit for their participation. Each participant was tested individually in a laboratory session lasting approximately 1 h. Participants performed two practice lists with letters and 10 lists of 10 words each followed by a surprise final free recall test. Words were 100 nouns selected from the Toronto word pool (Friendly, Franklin, Hoffman, & Rubin, 1982).

Procedure

Participants were tested individually. Items were presented alone for 1 s each. After list presentation, participants engaged in a 16 s distractor task before recall: Participants saw 8 three-digit numbers appear for 2 s each, and were required to write the digits in ascending order (e.g., Rohrer & Wixted, 1994; Unsworth, 2007). At recall participants saw three question marks appear in the middle of the screen. Participants had 45 s to recall as many of the words as possible in any order they wished from the current trial. Participants typed their responses and pressed Enter after each response clearing the screen. Prior to the practice and real trials, participants received a brief typing exercise (typing the words one-ten) to assess their typing efficiency. Immediately after the recall period for the last list, participants were told that their task was now to recall all of the words from all the lists in any order they wanted. They were instructed that they would have 5 min for recall and that they should continue attempting to recall new words throughout the entire 5 min.

Results and discussion

The results are divided into two sections: one section for delayed free recall and another section for final free recall. Each section was further subdivided into sections for analyses devoted to correct recalls, error responses, and latencies associated with each.

Delayed free recall

Correct recalls

Overall participants recalled roughly half of the presented items ($M = .53$, $SD = .09$). Fig. 2 shows standard serial position (Fig. 2a), probability of first recall (PFR; Fig. 2b), and lag-recency functions (Fig. 2c). The resulting serial position curve was consistent with previous research (Glanzer & Cunitz, 1966) demonstrating large primacy effects and small to nonexistent recency effects. Shown in Fig. 2b is the PFR curve. PFR refers to the number of times the first word recalled comes from a given serial position divided by the number of times the first recalled word could have come from that serial position. For instance, if a person begins recall with the last presented word nine out of ten times, then the probability of first recall for that serial position would be .90. The PFR curve suggested that participants began recall with the first word presented most of the time (63% of the time). Shown in Fig. 2c are the lag-recency functions for forward and backward transitions. These functions represent the conditional response probability (CRP) of forward and backward transitions made between correctly recalled items based on the presentation lag. These CRP functions were calculated exactly the same way as previous research has done (Howard & Kahana, 1999; Kahana, 1996). Consistent with this previous research (Howard & Kahana, 1999; Kahana, 1996) the majority of transitions were of a lag of 1 and in the forward

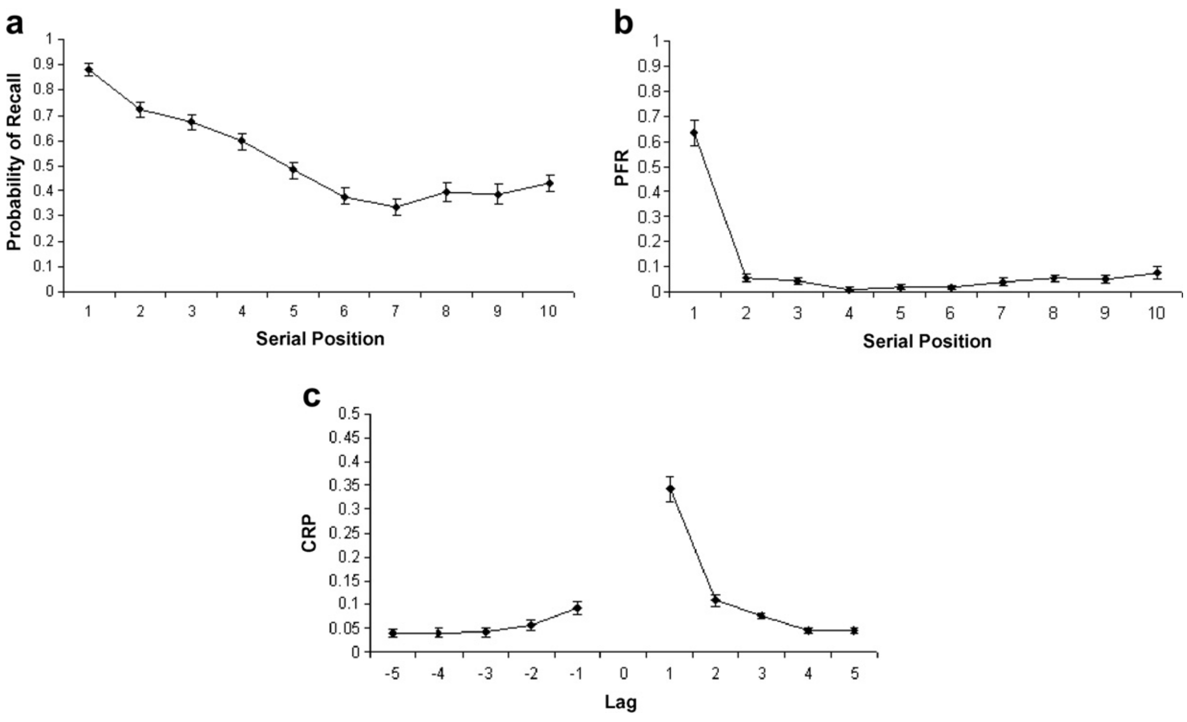

Fig. 2. (a) Probability of correct recall as a function of serial position. (b) Probability of first recall (PFR) as a function of serial position. (c) Conditional response probability functions for forward and backward transitions per list as a function of lag. Error bars represent one standard error of the mean.

direction. Specifically, forward transitions were more likely than backward transitions, $F(1,31) = 41.96$, $MSE = .01$, $p < .01$, partial $\eta^2 = .58$, transitions associated with a short lag were more likely than transitions associated with a long lag, $F(4,124) = 90.13$, $MSE = .004$, $p < .01$, partial $\eta^2 = .74$, and these two factors interacted suggesting that the lag effect was stronger in the forward than backward direction, $F(4,124) = 33.02$, $MSE = .17$, $p < .01$, partial $\eta^2 = .52$. Thus, participants tended to begin recall with the first word presented in a list and then tended to recall items in the forward direction leading to large primacy and virtually no recency effects.

Error responses

Next, error responses were examined to better understand the recall process. Errors were classified as previous list intrusions (items from previous lists; PLIs), extralist intrusions (items not presented on any other list; ELIs), or repetitions (items from the current list that had already been recalled). Shown in Table 1 is the average number of each error type per list. As can be seen the most frequently occurring error was ELIs followed by PLIs and repetitions. There were significantly more ELIs than either PLIs or repetitions, $F(2,62) = 21.68$, $MSE = .03$, $p < .01$, partial $\eta^2 = .41$, but there was no difference between PLIs and repetitions, $F(1,31) = 2.23$, $MSE = .06$, $p > .14$, partial $\eta^2 = .07$.

Examining each error type in more depth suggests a number of interesting findings. In terms of PLIs, on average these intrusions came from two lists back ($M = 1.82$, $SD = .94$). As shown in Fig. 3 and consistent with previous research (Murdock, 1974; Unsworth & Engle, 2007; Zaromb et al., 2006), the majority of these intrusions came from the immediately preceding list and the likelihood of an intrusion decreased as a function of lag. Additional examination of these errors suggested that many of them came from either primacy or recency positions on the list they were presented on. Specifically, 40% of all PLIs came from the first three serial positions on the list they were presented on, 34% came from the last three serial positions from the list they were presented on, and the remaining 26% of PLIs came from midlist positions. Furthermore, the majority of these errors were emitted near the end of each participants' recall with 35% of all PLIs occurring at the last output position and 65% of all PLIs occurring at one of the last three output positions. Roughly 22% of PLIs were also emitted at one of the first three output positions (14% being emitted at the very first output position) and the other 13% of PLIs were spread out among the remaining output positions. Thus, when a PLI was emitted it tended to occur predominantly near the end of recall and tended to come from either primacy or recency positions.

Similar to PLIs, the majority of ELIs were emitted near the end of each participants' recall with 27% of all ELIs occurring at the last output position and 60% of all ELIs occurring at one of the last three output positions. Roughly 20% of ELIs were also emitted at one of the first three output positions (only 4% being emitted at the very first output position) and the other 20% of ELIs were spread out among the remaining output positions. Similar to PLIs, when an ELI was emitted it tended to occur near the end or at the beginning of recall. Finally, in terms of repetition errors, roughly two intervening items ($M = 2.33$, $SD = 1.79$) separated the repetition from the initial correct response. Thus, an examination of error responses suggested that, like correct recalls, there were a number of systematic effects associated with errors.

Latency measures

In addition to the above measures on correct recalls and error responses, latency and IRT information associated with each was also examined to better understand the dynamics of delayed free recall. Previous research has shown that an examination of overall recall latency as well as inter-response times (IRTs) provides a window into the search process (Rohrer & Wixted, 1994; Unsworth, 2007; Wixted & Rohrer, 1994). Shown in Fig. 4 is the cumulative recall curve averaged across lists. This curve represents the cumulative number of items recalled at each second during the 45 s recall period and provides an overall depiction of

Table 1
Mean number of each error type per list for delayed free recall

PLI	ELI	Repeat
16 (.15)	.36 (.26)	.11 (.16)

Note. PLI, previous list intrusion; ELI, extra-list intrusion; repeat, repetition error. Numbers in parentheses are standard deviations.

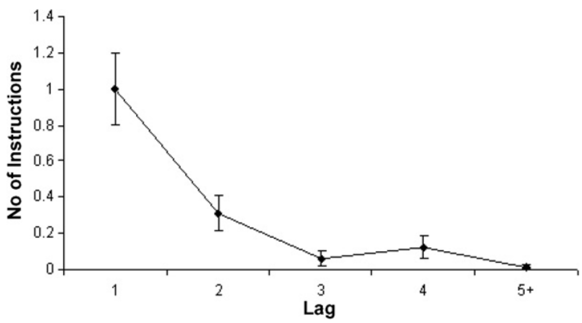

Fig. 3. Number of previous list intrusions (PLIs) as a function of lag (list). Error bars represent one standard error of the mean.

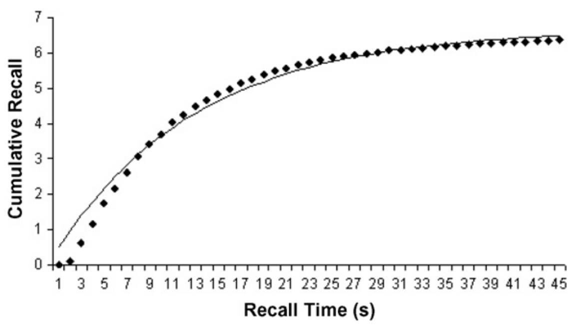

Fig. 4. Cumulative recall curve as a function of recall time. Symbols represent the observed data and the solid line represents the best fitting exponential.

the full time course of recall during the recall period. Consistent with previous research (Rohrer & Wixted, 1994; Wixted & Rohrer, 1994), the cumulative recall curve is well described by a cumulative exponential

$$F(t) = N(1-e^{-\lambda t}),$$

where $F(t)$ represents the cumulative number of items recalled by time t, N represents asymptotic recall, and λ represents the rate of approach to asymptote. As shown in Fig. 4 the symbols represent the data and the line represents the best fitting cumulative exponential. The resulting parameter estimates were $N = 6.68$ and $\lambda = .08$. Additionally, the fit was acceptable with the function accounting for 98% of the variance and Kolmogorov–Smirnov tests were non-significant ($p > .61$). A number of interesting findings emerge upon inspection of the figure. First, as noted by Rohrer and Wixted (1994) there is a distinct pause (lasting more than a second) between the onset of the recall period and when participants actually begin recalling. Second, most items are recalled within the first 15 s of the recall period, with only a few items being emitted after that. Third, the rapid rise of the function within the first 15 s suggests that items are being recalled in rapid succession with relatively short IRTs between the words.

Although the cumulative recall curve provides a general depiction of recall latency, a more detailed analysis of recall latency and IRTs is necessary to more fully understand recall dynamics. Therefore, recall latency and IRTs for correct recalls and error responses were examined in more detail. Note that recall latency refers to the time point in the recall period when a given response was emitted. Thus, if responses were emitted 5, 10, and 15 s into the recall period, mean recall latency would be 10 s. On average the first item was emitted 3.74 s ($SD = 1.44$) after the onset of the recall signal consistent with the notion of a pause preceding output. Overall, average recall latency was 11.02 s ($SD = 2.86$) suggesting that, on average, participants emitted their responses 11 s into the recall period. This, however, differed for correct and error responses. On average, correct recalls were emitted earlier in the recall period ($M = 9.84$ s, $SD = 2.78$) than error responses ($M = 17.00$ s, $SD = 4.29$), $t(31) = -9.10$, $p < .01$. Breaking down recall latency for each of the error types suggested that both PLI ($M = 15.59$ s, $SD = 6.22$) and ELI ($M = 16.23$ s, $SD = 8.01$) errors were emitted earlier in the recall period than repetition errors ($M = 23.85$ s, $SD = 10.48$; both p's $< .05$). Overall, these results are consistent with the output position analyses suggesting that errors are usually emitted late in the recall period (see also Craik, 1968).

Next IRTs were examined. IRTs were measured as the difference between the first key stroke on item n and the first key stroke on item $n + 1$. An examination of IRTs suggested that IRTs associated with correct recalls were faster ($M = 3.13$ s, $SD = 1.04$) than IRTs associated with errors ($M = 5.43$ s, $SD = 3.48$), $t(31) = -3.78$, $p < .01$. Furthermore, in terms of correct recalls, IRTs associated with forward transitions were faster ($M = 2.88$ s, $SD = 1.11$) than IRTs associated with backward transitions ($M = 4.00$ s, $SD = 1.76$; $t(31) = -3.14$, $p < .01$). Thus, not only were forward transitions more likely than backward transitions, but they were also faster as well. Breaking down the IRTs associated with errors suggested that all IRTs were fairly close to the average error IRTs (M PLI = 5.75 s, $SD = 3.49$; M ELI = 5.05 s, $SD = 3.78$; M Repeat = 6.41 s, $SD = 6.49$).

Summary

Overall, these results are consistent with prior work examining retrieval dynamics in delayed free recall (Howard & Kahana, 1999; Rohrer & Wixted, 1994; Unsworth, 2007). Specifically, individuals typically begin recall with the first presented word (leading to large primacy effects and then recall words that were presented in close temporal proximity thereafter. Furthermore, individuals tend to output most of the recalled items early in the recall period with short IRTs between items early on. Later in the recall period, the search for new items becomes more laborious resulting in longer IRTs and several errors. In particular both PLIs (which typically came from primacy and recency positions from the immediately preceding list) and ELIs tend to occur late in the recall period and are associated with much longer IRTs than correct recalls. These longer IRTs likely reflect an increase in the amount of time searching for new items as well as additional time needed to monitor potentially unsure responses. Finally, consistent with many sampling models the overall cumulative recall

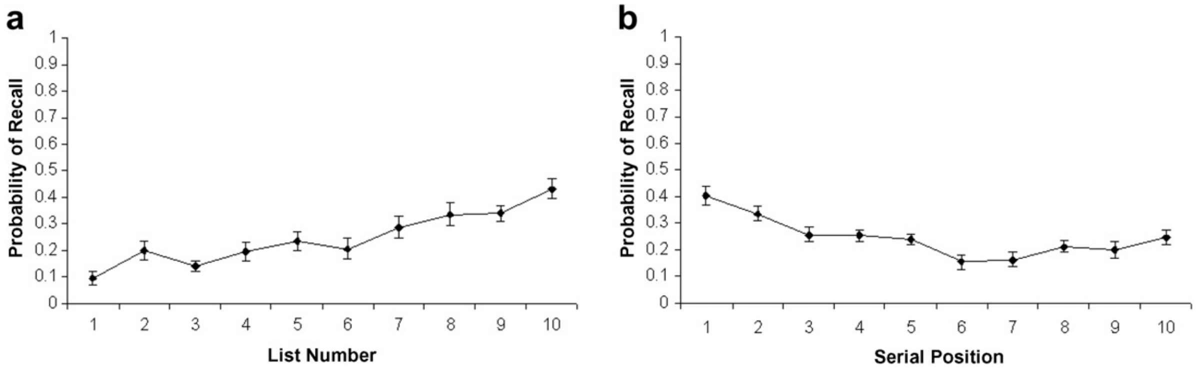

Fig. 5. (a) Probability of correct recall as a function of list number. (b) Probability of correct recall as a function of serial position. Error bars represent one standard error of the mean.

curve was well described by a cumulative exponential and individuals tended to emit repetition errors late in the recall period. Note, that many of these effects have been reported previously in the literature, but it was important to demonstrate them here in order to examine the extent to which within list final free recall and single trial delayed free are similar.

Final free recall

Correct recalls

Overall participants recalled roughly a fourth of all of the presented items ($M = .25$, $SD = .09$). Shown in Fig. 5 are list (Fig. 5a) and serial (Fig. 5b) position functions for final free recall. Consistent with previous research (Glenberg et al., 1980), most words recalled came from the last presented list, and fewer words were recalled from the first lists presented. Additionally, and consistent with the serial position functions from delayed free recall, there was a strong primacy advantage apparent in the serial position functions for final free recall. Thus, participants tended to recall items from the most recently presented lists, and they tended to recall items presented early in the list than items presented late in the list. Shown in Fig. 6 are PFR functions for lists (Fig. 6a) and items (Fig. 6b). As can be seen participants tended to begin recall with the last presented list and overall there was a strong recency trend similar to list position functions. In terms of items, participants tended to begin recall with the first word in a list very similar to the delayed free recall findings. Thus, it seems that there are strong recency effects for lists, but strong primacy effects for items within a list.

Next, lag-recency effects for both lists and items within a list were examined. Shown in Fig. 7a are the lag recency functions for transitions between lists. Here it can be seen that when transitions were between lists it was more likely to transition to a list presented in close proximity to the current list than to transition to lists further away (see Howard, Youker, & Venkatadass, 2008 for similar results). However, unlike delayed free recall, the forward bias was much smaller and the lag recency functions for forward and backward transitions were quite symmetrical. Specifically, forward transitions were more likely than backward transitions, $F(1,31) = 5.29$, $MSE = .06$, $p < .05$, partial $\eta^2 = .15$, transitions associated with a short lag were more likely than transitions associated with a long lag, $F(4,124) = 4.83$, $MSE = .08$, $p < .01$, partial $\eta^2 = .14$, but these two factors did not interact, $F < 1$. An examination of within list transitions (i.e., transitions with a list lag of 0 only) suggested that items presented in close temporal proximity were more likely to be recalled in succession than items presented further away and there was a strong forward

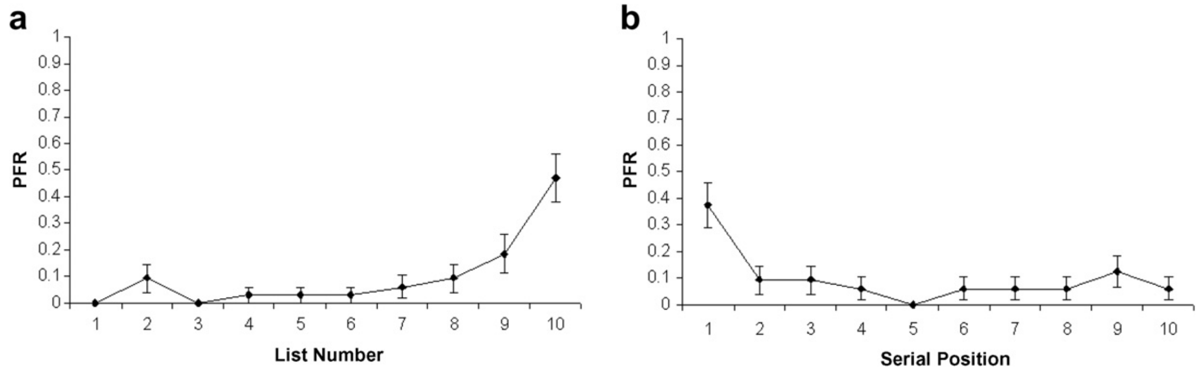

Fig. 6. (a) Probability of first recall (PFR) as a function of list number. (b) Probability of first recall (PFR) as a function of serial position. Error bars represent one standard error of the mean.

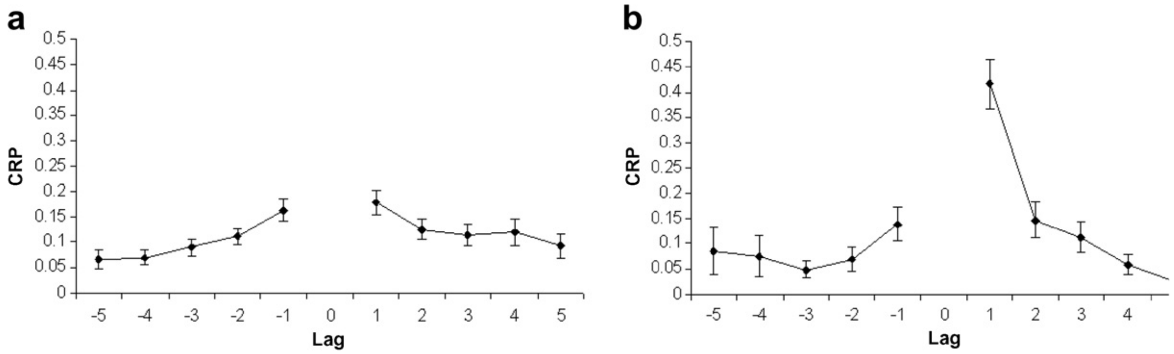

Fig. 7. (a) Conditional response probability functions for forward and backward list transitions as a function of lag. (b) Conditional response probability functions for forward and backward within list transitions as a function of lag. Error bars represent one standard error of the mean.

bias. Specifically, forward transitions were more likely than backward transitions, $F(1,26) = 7.44$, $MSE = .04$, $p < .05$, partial $\eta^2 = .22$, transitions associated with a short lag were more likely than transitions associated with a long lag, $F(4,104) = 14.79$, $MSE = .03$, $p < .01$, partial $\eta^2 = .36$, and these two factors interacted suggesting that the lag effect was stronger in the forward than backward direction, $F(4,104) = 7.04$, $MSE = .03$, $p < .01$, partial $\eta^2 = .21$. Note, these analyses are based on only 27 participants because one participant did not have any within list transitions, and four participants did not making any transitions of lag 5. Overall, within list transitions were very similar to transitions seen in delayed free recall.

Thus far these results are consistent with the notion that participants first sampled lists and then sampled items within a list very similar to results seen in category fluency tasks. This suggests that participants are clustering items based on temporal factors. In order to examine this more thoroughly, the overall number of within list clusters, the overall number of between list switches, as well as the average size of the within list clusters was calculated for each participant. Clusters here refer to successive recalls of items from the same list. These analyses suggested that on average participants had 5.19 ($SD = 2.26$) within list clusters, 14.28 ($SD = 5.26$) between list switches, and an average within list cluster size of 2.64 ($SD = .92$).

Error responses

As with delayed free recall, error responses were also examined to better understand the recall process. Errors were classified as either extralist intrusions (items not presented on any other list; ELIs), or repetitions (items from the current list that had already been recalled). Note, that previous list intrusions were no longer relevant given that words from all presented lists were counted as correct recalls. The analysis of errors suggested that participants recalled 6.84 ($SD = 5.18$) ELIs and 1.82 ($SD = 1.68$) repetitions. On average, 8.77 ($SD = 13.42$) words separated the repetition from the initial correct recall.

Latency measures

Finally, the same latency analyses that were carried out on delayed free recall were done on the final free recall data. Shown in Fig. 8 is the average cumulative recall function for final free recall along with the best fitting cumulative exponential. Note that responses were placed into sixty 5 s bins to represent the 5-min recall period. The resulting parameter estimates were $N = 35.95$ and $\lambda = .06$. Additionally, the fit was acceptable with the function accounting for 99% of the variance and Kolmogorov–Smirnov tests were non-significant ($p > .62$). As with delayed free recall a number of interesting features are apparent for the overall curve. First, like delayed free recall there is a distinct pause between the onset of the recall period and when participants actually begin recalling. Second, most items are recalled within the 125 s of the recall period, with only a few items being emitted after that. Third, the rapid rise of the function within the first 125 s suggests that items are being recalled in rapid succession with relatively short IRTs between the words, but these IRTs were much longer than those seen in delayed free recall given the much longer recall period.

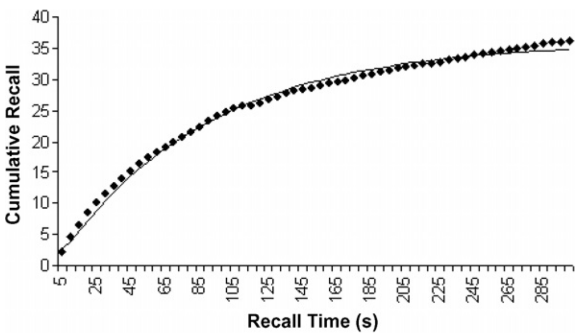

Fig. 8. Cumulative recall curve as a function of recall time. Symbols represent the observed data and the solid line represents the best fitting exponential.

To further examine the time course of retrieval, recall latency and IRTs were examined for correct and incorrect responses. Similar to delayed free recall, the first item was emitted 3.04 s ($SD = 1.63$) after the onset of the recall signal consistent with the notion of a pause preceding output. Overall, average recall latency was 82.29 s ($SD = 25.80$) and, again, this differed for correct and error responses. On average, correct recalls were emitted earlier in the recall period ($M = 68.66$ s, $SD = 24.29$) than error responses ($M = 107.70$ s, $SD = 36.36$), $t(31) = -6.73$, $p < .01$. Examining each error type separately suggested that ELI ($M = 108.06$ s, $SD = 49.32$) errors and repetition errors ($M = 96.16$ s, $SD = 86.43$) were both emitted late in the recall period.

An examination of IRTs suggested that IRTs associated with correct recalls were faster ($M = 6.24$, $SD = 2.07$) than IRTs associated with errors ($M = 8.61$, $SD = 3.91$), $t(31) = -3.46$, $p < .01$. Furthermore, in terms of correct recalls, within list (cluster) IRTs were faster ($M = 3.20$, $SD = 1.69$) than between list (switching) IRTs ($M = 8.16$, $SD = 3.18$), $t(30) = -7.48$, $p < .01$. Thus, very consistent with two-stage search models of verbal fluency, within cluster IRTs were faster than between clusters (switching) IRTs. Additionally, an examination of within list IRTs suggested that forward ($M = 3.17$ s, $SD = 2.20$) and backward transitions ($M = 4.12$ s, $SD = 4.11$) had similar IRTs and IRTs associated with forward ($M = 8.37$ s, $SD = 7.21$) and backward list transitions ($M = 8.96$ s, $SD = 5.63$) were also similar (both p's > .40. Breaking down the IRTs associated with each error suggested that both IRTs for ELIs ($M = 9.60$ s, $SD = 8.61$), and IRTs for repetitions ($M = 5.54$ s, $SD = 8.66$), were similar to one another and to the overall error IRTs (both p's > .14).

Output order effects based on initial delayed free recall

The final set of analyses examined the extent to which items recalled initially in delayed free recall were recalled again in final free recall or whether new items were recalled. Similar to previous studies (Craik, 1970) the majority (i.e., 89%) of items recalled in the final free recall test were also initially recalled in the delayed free recall test. Further examination of these items suggested that items were recalled in the final free recall test in part based on the output order from the initial delayed free recall test.

That is, instead of examining input position in the delayed free recall test, here output position from the initial recall test is examined. Given that delayed free recall participants generally begin recall with the first presented word and then transition to words that were presented close together, the input and output position analyses will be highly correlated, but an examination of output order effects based on initial delayed free recall can still provide potentially interesting information. Specifically, as shown in Fig. 9a, the majority of items recalled in the final free test that were initially recalled in the delayed free test came from one of the first 4–5 output positions in delayed free recall. This isn't surprising given that participants tended to only recall about five words in the initial delayed free recall test, thus there are few possibilities to recall items from higher output positions. Additionally, participants began recall with the first outputted word from delayed free recall (Fig. 9b) and the next item recalled tended to come from a nearby output position in the delayed free recall test (Fig. 9c). Like initial delayed free recall and within list transitions this effect demonstrated a distinct asymmetry with a forward bias. Specifically, forward transitions were more likely than backward transitions, $F(1,27) = 6.47$, $MSE = .004$, $p < .05$, partial $\eta^2 = .19$, transitions associated with a short lag were more likely than transitions associated with a long lag, $F(4,108) = 36.62$, $MSE = .004$, $p < .01$, partial $\eta^2 = .58$, and these two factors interacted suggesting that the lag effect was stronger in the forward than backward direction, $F(4,108) = 10.79$, $MSE = .004$, $p < .01$, partial $\eta^2 = .29$. Note, these analyses are based on only 28 participants because four participants did not making any transitions of lag 5. Additionally, these transitions tended to occur in runs of roughly 2.6 items. That is, participants tended to cluster items based on their initial output order in delayed free recall. These output order effects suggests that final free recalls are based not only on the initial presentation order of the items in delayed free recall, but also on the output order of these items.

Summary

Overall, the final free recall results suggest a number of interesting systematic effects. For instance, the results suggested that participants tend to begin recall with the last list presented, but the first word presented from that list. Furthermore, once an item was recalled from a list, the next item recalled tended to be from that same list leading to a large number of within list transitions. Similar to delayed free recall, within list lag-recency effects suggested that items presented in close temporal proximity tended to be recalled together and there was a strong forward bias. These within list transitions tended to occur as clusters of roughly 3 items. These items were associated with relatively fast IRTs which were much faster than IRTs associated with items between lists. Thus, after a cluster was emitted, participants then switched to a new list of items which took some time. The new list that participants switched to was typically a list that was presented in close temporal proximity to the previous list, but unlike delayed free recall (or recall within a list) transitions between lists

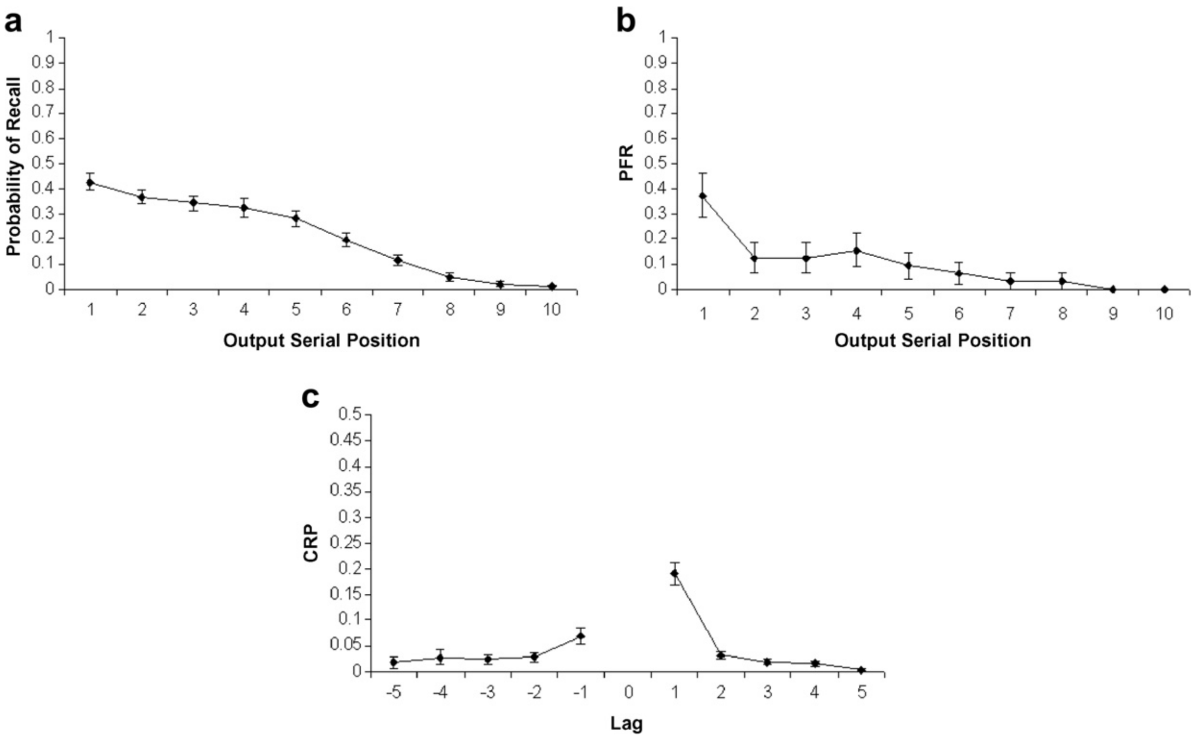

Fig. 9. (a) Probability of correct recall as a function of output serial position in the initial delayed free recall test. (b) Probability of first recall (PFR) as a function of output serial position in the initial delayed free recall test. (c) Conditional response probability functions for forward and backward transitions for output positions in the initial delayed free recall test as a function of lag. Error bars represent one standard error of the mean.

were equally likely in the forward and backward direction. Across the board, within list effects tended to be very similar to the effects seen with delayed free recall, whereas between lists effects were typically different (e.g., serial position, PFR, lag-recency, etc.). Additionally, as with delayed free recall, individuals tended to emit most of the recalled items early in the recall period with short IRTs between items early on, although these IRTs were much longer than those seen with delayed free recall. As recall proceeded, the search process began to break down leading to longer IRTs and more errors. In particular both ELI and repetition errors occurred late in the recall period and were associated with longer IRTs than correct recall IRTs. Finally, an examination of final free recall based on initial delayed free recall suggested that the majority of items recalled in the final free recall test were initially recalled in the delayed free recall test. Further examination of the output order effects based on initial delayed free recall suggested that participants tended to recall items based on the output position such that items recalled in close proximity initially tended to be recalled in the same order on delayed free recall.

General discussion

The goal of the current investigation was to examine the dynamics of retrieval from episodic memory in both delayed and final free recall. Specifically, the current study examined the extent to which a two-stage hierarchical sampling framework based on temporal-contextual cues would be able to account for systematic effects found in delayed and final free recall. In this framework it is assumed that items are associated with contextual elements from different levels in a hierarchy (i.e., Global, List, and Word contexts). At retrieval it is assumed that first a list is sampled based on the associative strength between the list context and the global context. In delayed free recall it is necessary to sample only the most recently presented list, thus there is a strong bias to use recent temporal context as cues. This is also seen in final free recall where typically the last list presented was the first list recalled. Thus, the sampling of lists seems to rely on recency information.

Once a list has been sampled, it is assumed that items within the list are sampled based on the associative strength of the word (or item) context to the list context. In delayed free recall it was found that the first presented item tended to be the first recalled item. Thus, unlike sampling for lists, it seems that sampling for items is not based on recency information. Rather, it seems that the associative strength of words to the list context is based on something like rehearsal or attention at encoding. After the first item in a list has been recalled, it is assumed that the recalled item along with the list context will be used to cue the next item. Consistent with this, there were strong lag-recency effects where items presented in close temporal proximity tended to be recalled in close proximity and there was a strong forward bias. Thus, participants tended to begin recall with the first presented item and then recall proceeded in the forward direction leading to strong primacy effects and reduced recency effects. Similar effects were found in final free recall. Specifically, participants tended to recall items in clusters based on which list the items were presented in. Recall of within list items tended to begin with the first presented list item and proceed in the forward direction. Thus, the results for delayed free recall and final free recall within list effects were remarkably similar, suggesting a similar retrieval process occurring in both.

In final free recall, in the two-stage search framework it is assumed that once clustered items are produced, retrieval reverts back up to the list level and a new list must be sampled. In the framework it is assumed that sampling of lists after the first sampled list is very similar to sampling of items. In particular, it is assumed that a new list is sampled based on both the global context and the list context from the last recalled list. As with items this suggests that there should be a lag-recency effect whereby lists presented in close proximity should be recalled in close proximity. Consistent with this, strong lag-recency effects for lists were found. However, unlike the lag-recency effect for items, there was not a strong forward bias for list lag-recency, rather forward and backward list transitions were equally likely. However, it should be noted that different patterns of results are possible depending on the recall task used. For instance, if immediate of continuous distractor free recall had been used instead of delayed free recall, one would expect larger recency effects and different PFR functions. Additionally, one might expect slightly different final free recall results if a distractor task had been given between recall of the last list and the final free recall test. Future work is needed to better examine these effects across a range of free recall tasks.

An examination of the items recalled in the final free recall test suggested that most of these items were initially recalled on the delayed free recall test and only a few were new items that were not initially recalled were emitted (Craik, 1970). This is consistent with previous work that that has suggested that the act of recalling an item serves to strengthen that item making it easier to recall in the future (e.g., Rundus, 1973). Further examination of these items based on output order effects suggested that participants tended to begin their final free recall based on a word from the first output position in delayed free recall consistent with finding that this item tended to also be from the first presentation position. Additionally, an examination of the output CRP functions suggested that participants tended to recall items that were recalled in succession initially and these items tended to be recalled in clusters of roughly 2.6 items. This suggests that not only were individuals using the initial presentation context of items as a cue but they were also using the recall context of the items as a cue. That is, the act of recalling an item served not only to increase the strength of that item, but it also served to associate items recalled in a succession with an overall representation of recall context leading to possibly greater encoding variability and hence better retention (Bower, 1972). Although it should be noted that input and output positions are likely highly correlated in the current situation and thus future research is needed to better examine the possibility that the act of recalling an item leads to the association of items to the recall context which then serves as a cue for future retrieval operations. In particular, it would be interesting to examine these output CRPs in final free recall after an immediate free recall test given that recall order should change from intial to final free recall or when output order is manipulated (Dalezman, 1976).

Examinations of latency measures in both delayed and final free recall were also consistent with a two-stage search framework. In particular, cumulative recall curves in both were well described by a cumulative exponential suggesting that as the recall period progressed, there were fewer and fewer items recalled. Additionally, IRTs associated with forward transitions in both delayed free recall and within list clusters in final free recall were faster than IRTs associated with backward transitions. Both forward and backward list transitions in final free recall, however, were equally fast. Once again this suggests slightly different retrieval dynamics associated with within list/delayed free recall and between list recall. Indeed, within list (cluster) IRTs were faster than between list (switching) IRTs. Importantly, between list (switching) IRTs were nearly double that of within list (cluster) IRTs. This is consistent with a two-stage search framework in that when switching between clusters first a list must be sampled and then an item within a list must be sampled. There may also be additional time associated with between list IRTs due to extra time needed to exit a cluster (see for example Patterson, Meltzer, & Mandler, 1971).

Examination of errors in both delayed and final free recall suggested that extra-list (ELIs) and repetition errors tended to occur later in the recall period than correct recalls and were typically associated with longer IRTs than correct recalls. Furthermore, consistent with temporal-contextual theories of free recall, a number of errors in delayed free recall were previous list intrusions (PLIs) which tended to come from the immediately preceding list. These errors tended to occur late in the recall period and where associated with long IRTs. This suggests the possibility that as the recall period progressed and no new items were being recalled, participants may have extended their search further back in time and started to sample items from the previous list. As with the between list IRTs in final free recall, PLI IRTs should be longer than correct recall IRTs given the additional time needed to sample a new list and an item within that list, which was the case. Additional time would also likely be needed on these items given additional monitoring that would be needed. Finally, it is interesting to note that many of the PLIs came from primacy portions of the immediately preceding list, in line with the two-stage search framework.

Relation to other work

Overall the current results suggest that in many episodic memory tasks where unrelated words are used, participants rely heavily on temporal context to search for items. Furthermore, the current results are consistent with the notion that episodic memory is organized based on a temporal dimension and this organization can have multiple levels (Brown et al., 2000, 2007; Glenberg et al., 1980, 1983; Unsworth & Engle, 2007). As noted previously, the notion that remembering is based in part on temporal context has a long history and is important in many theories of free recall performance. Indeed, the notion of temporal context has been used to explain recency effects in the continuous distractor task, lag-recency effects that are found in a number of paradigms, as well as proactive interference effects. The current study builds on these findings by demonstrating that temporal context seems to play a role in final free recall whereby individuals tend to recall clusters of within list items that were presented close together in time originally. This suggests that in episodic free recall tasks, individuals organize items based on shared temporal context and then at retrieval rely on the overlapping temporal context (from different levels) to retrieve different lists and items within a list.

The current data and framework are broadly consistent with a number of models that rely on temporal-contextual cues to retrieve items from episodic memory as noted previously. In particular, given that the current framework is based on previous models of contextual retrieval (Glenberg et al., 1983; Howard & Kahana, 1999, 2002b) these models would readily account for the current results. Specifically, models such as the Temporal Context Model (TCM; Howard & Kahana, 2002b) suggest that once an item is retrieved, the context that is associated with that item is used as a cue for the next item and so on. Thus, as Howard and Kahana (2002b) have noted, this model readily predicts the lag-recency effect in many situations and across many time scales. As noted previously, Howard et al. (2008) have recently demonstrated a lag-recency effect for lists consistent with the current results. Howard et al. suggest that this effect is consistent with context retrieval models such as TCM because in TCM items are associated with a varying context signal and then context can serve as a cue for the retrieval of items associated with similar contexts regardless of time scale. Clearly, the results of the current study and the basic two-stage search framework are consistent with this suggesting that items are associated with multiple levels of temporal context all of which can serve as a cue in the future regardless of the time scale.

Having said that, it would be remiss not to point out that the current results and those of Howard et al. (2008) are not consistent with other episodic associative models. As noted by Kahana, Howard, and Polyn (2008) other episodic associative models such as chaining models, buffer models, and hierarchical association models, can not readily account for the lag-recency effect for lists as they are currently structured. For instance, as noted by Kahana et al. buffer models account for the lag-recency effect by assuming that items that are coactive in the short-term buffer build-up item-item associations at encoding. Later, these items can be recalled in succession due the item-item strengths. However, these models have trouble accounting for the list lag-recency effect given that the buffer is usually very limited in size and thus items from different lists would not be coactive in the buffer at the same time. Thus, as it currently stands, models such as SAM (Raaijmakers & Shiffrin, 1980) and the context-activation model (Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005) should not be able to account for this effect. Although, it may be possible to augment these buffer models by suggesting that at encoding each item in the buffer is associated not only with the other items in the buffer but also with the different levels of context within a hierarchical framework as suggested previously. These higher-order associations might then be used during retrieval to cue items from nearby lists similar to the current framework.

Finally, it should be noted that the current framework was not meant to be an alternative to contextual retrieval models such as TCM, rather the purpose of the current study was to show that a two-stage search framework that has been used in other research domains (such as semantic and autobiographical memory) could be used to understand the dynamics of recall in episodic memory tasks. The difference between the current framework and previous models is that here it is assumed that clusters and items within clusters are based not on semantic relations, but rather are based on temporal-contextual relations. This suggests a general two-stage (or multi-stage) search framework can be used to explain retrieval in a number of different domains that may differ only in the content of the desired information and in the cues used to access the desired information. That is, the two-stage search framework can be used to examine retrieval in verbal fluency tasks where information is retrieved based on semantic relatedness and individuals rely on semantic cues to access items. The same two-stage search framework can also be used to retrieve items in episodic free recall tasks where items are associated based on the overlap in temporal context and temporal-contextual cues are used to access items. The same framework can also be used to retrieve autobiographical memories that may be associated on a number of dimensions such as shared temporal context (e.g., my time spent in college) and/or shared themes (e.g., classes I have taken throughout my education) and these are used as retrieval cues during the search process (see for example Williams & Hollan, 1981). Thus, it is possible that a general search process is used to retrieve items from memory despite differences in the content of the memories. Future work should be directed at examining how a general search model can be used to retrieve multiple types of memories.

Conclusion

The current study examined the dynamics of retrieval in delayed and final free recall. It was found that in both delayed free recall and within list clusters in final free recall that participants begin recall with the first presented item and then tended to recall items in a forward direction leading to large primacy and small recency effects. In final free recall within list transitions were prominent (within list clusters) and when switching to a new list participants tended to recall lists that were presented in close temporal proximity to the current list leading to a list lag-recency effect. These results along with results for error responses and latency measures were consistent with a two-stage search framework that relies on temporal-contextual cues. Overall, the results suggest that in episodic free recall tasks in which lists consist of unrelated words, first lists are sampled and then items within a list are sampled based on temporal-contextual cues. This two-stage search process is broadly consistent with search models of memory in other domains and suggests, perhaps, that a general search scheme is used to retrieve information regardless of the content of the memories.

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