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Chunking in Backward Recall of Digits: An fMRI study

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Background

Working memory is the mind's sketchpad for mental storage and manipulation of information (Miller et al., 2018). It is crucial to everyday tasks such as recalling PINs and passwords, mental mathematical manipulations, and learning new sequences of action. Dysfunction of this executive function is detrimental to these everyday tasks and significantly lowers the quality of life, as seen in patients living with schizophrenia, multiple sclerosis, and traumatic brain injury (Forbes et al., 2008; Litvan et al, 1988; McDowell et al., 1997). Therefore, understanding the mechanisms underlying working memory is crucial to having a better understanding of these disorders.

In most working memory applications, the order of recall is important. When memory content is recalled, it can be recalled in the same order it was presented (forward recall) or the reverse order (backward recall). Backward recall, despite being uncommon in everyday life, is widely used in research and clinical settings. For instance, backward digit span (backward recall of digits) has been used in psychological research as a measure of working memory for children, adults, and the elderly populations (Elliott et al., 1990; Wechsler, 2014). It has strong correlations with current and future academic performance for children and has shown strong sensitivity to age-related cognitive decline (Bull et al., 2008; Bopp & Verhaeghen, 2005). Thus, it has been an area of interest to determine the mechanism behind backward recall.

Behavioural Studies

Earlier behavioral studies have aimed to propose models of backward recall. In 1965 Conrad proposed that a series of forward recalls would be adequate to simulate backward recall. Since then, many studies have tried to test this theory, and found promising results in backward recall of digits and words (Anders & Lillyquist, 1971; Anderson et al., 1998; Bireta et al., 2010). Yet, other studies sparsely observed this effect, and suggested that alternatively retrieval could operate with equal facility in both forward and backward recall (Norris et al., 2019, Farrand & Jones, 1996; Thomas et al., 2003). Despite the importance of backward recall for research, the evidence for its mechanism has been inconclusive.

The variability in the evidence could be due to the various strategies participants use to aid working memory. It has been known that there are limits to working memory span (Brener, 1940), and studies have determined this limit to be approximately six digits for numbers (Miller, 1956; Norris et al., 2019). As the cognitive load approaches or exceeds the limit, participants use mnemonic devices, or strategies to aid memory. There are several techniques identified in the past that could be utilized to recall numbers, with one of the most common being chunking. In this study, we aim to investigate two models of backward recall, considering chunking.

First described by Miller (1956), chunking is a cognitive tool in which large sequences of items are grouped together in smaller subsets, as often used with digits (Ex: Phone Numbers: 6479898456 to (647)-9898-456) (Solopchuk et al., 2016, Popp et al., 2019). Chunking has been thought to decrease the load on working memory by bypassing its limit through utilizing long-term memory, freeing capacity for subsequent encoded material (Thalmann et al., 2019). For instance, it has been shown that chunking method can effectively improve performance (accuracy and response time) in verbal working memory tasks in Alzheimer's disease patients (Huntley et al., 2018). Additionally, this cognitive tool for working memory can influence motor performance as well. Participants asked to memorize a digit sequence and immediately recall using a finger press keyboard, tend to take longer pauses between chunks than pauses within each chunk (Verwey, 1996; Popp et al., 2020). Independent of the chunking strategy used, the pause times between presses, Inter-press Intervals (IPIs), can reflect the chunking method utilized by comparing between-chunk and within-chunk IPIs. Furthermore, chunking strategies could be induced, by presenting the items within a chunk simultaneously and closer together (Ex: 6479898456 could be presented as 647 989 8456) (Mclean & Gregg, 1967).

In a previous behavioral study, we tested between two models of backward recall, and we observed that the peel-off model more accurately represented the data. The peel-off model is based on the assumption that a series of forward recalls are performed to carry out backward recall. As shown in Figure 1A, in the peel-off model items are stored in a working memory storage, only accessible from the top. In forward recall without chunking, individual items are recalled in serial order from the top. However, backward recall requires performing a series of peel-offs (forward retrievals) and recalling the last item. In each successive peel-off, there is one less item being peeled off; thus, one less operation is performed, making the task progressively easier. In the last recall, there is no need for a peel-off as there will only be one item left in memory.

When chunking is considered each chunk acts as a smaller memory unit, following the same operations as the main storage (Figure 1B). In forward recall with chunking, first chunks are retrieved from the top, and then items within each chunk are accessed from the top. In backward recall, the peel-off strategy is performed both for chunks and within each chunk. First, all the chunks except the last chunk are peeled off and the last chunk is retrieved. To reverse the item order within the chunk, all the items except the last item are peeled-off, and the last item is recalled. This is performed first for all the items in the last chunk and then for the other chunks. Thus, the operations in this model are recalling single items, recalling single chunks, peeling-off items, and peeling-off chunks.

As shown in Figure 1C & D, the peel-off model makes specific predictions based on the operations required for each recall. This model predicts a slower average response time in backward recall compared to forward recall in both chunking conditions. In terms of overall accuracy, the peel-off model predicts that recall in the backward direction will be less accurate than forward recall.

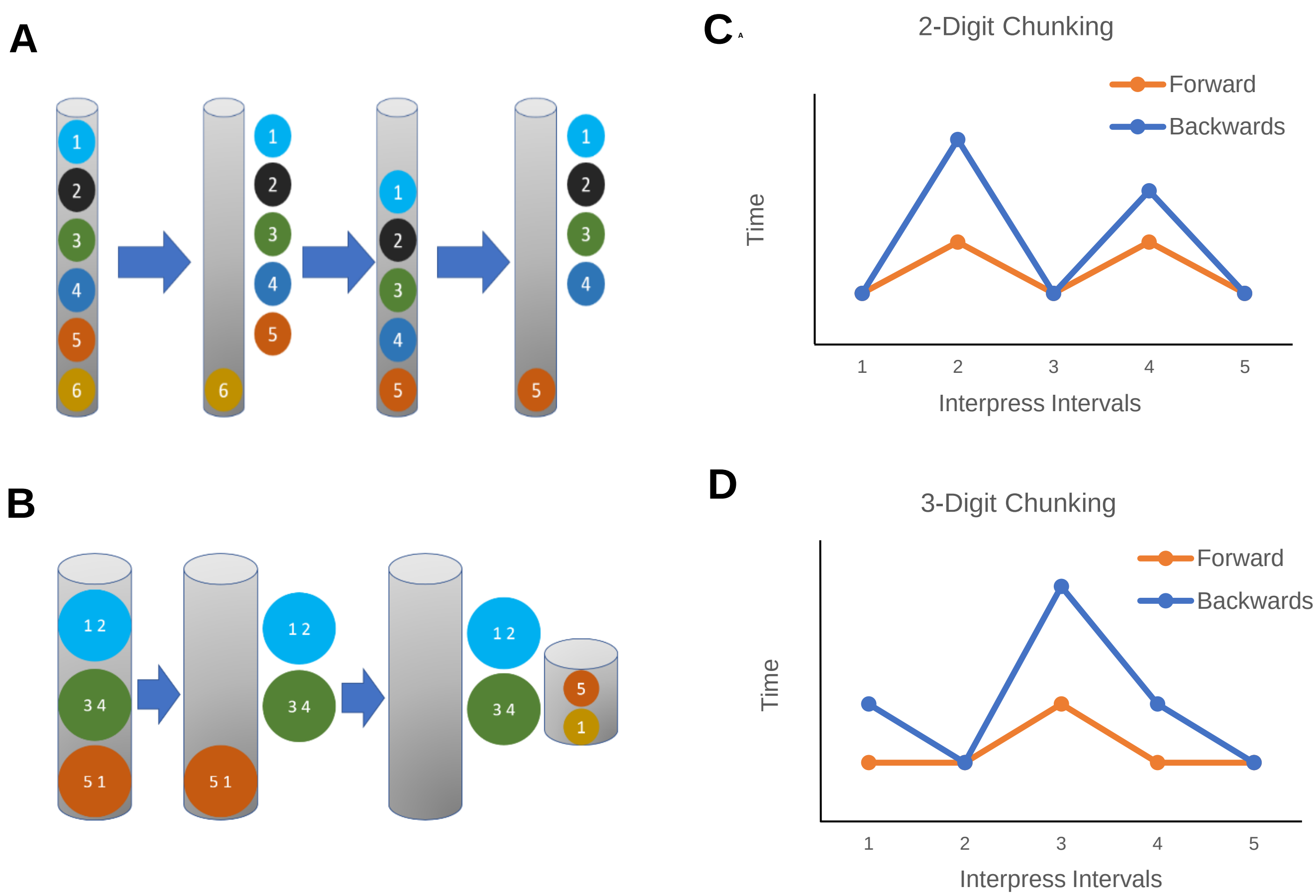

Figure 1. Visual representation of the peel-off model. A: The items are stored in the main storage (large grey cylinder) and could be only accessed from the top (forward direction). In the first round, all items except the last item will be retrieved (peeled-off), and the last item (6) is recalled. Then all item except the second last item (5) are peeled-off and the item is recalled. This will continue for all items, where every time n-1 number of items are peeled-off; thus, the task gets easier progressively over time. **B:** When Chunking is considered (example based on 2-digits), first all but the last chunk are peeled-off and the last chunk is recalled. However, to reverse the order within the chunk, peel-off has to be performed for the items within the chunk. **C&D:** Interpress intervals based on this model

Our behavioral results showed three important findings. First was that the inter-press interval patterns were most similar to those predicted by the peel-off model. Second, we showed that overall performance was lower in backward recall. Lastly, we showed that chunking by 3-digits was more accurate and faster than the 2-digit chunking condition. This finding suggested that number of chunks is more important in recall performance than chunk size. This was in line with previous research (Chen & Cowan, 2005; Thalmann et al., 2019) proposing that chunking memory perforamnce benefits are independet of chunk size. Moreover, this is in support of the fixed-chunk hypothesis (Brener, 1940; Miller, 1956) which posits that there might be a fixed number of chunks allowed in working memory, where more items can be stored by using larger chunks.

Imaging Studies

Although there has not been a consensus on a model for backward recall or working memory, there have been studies exploring the neural correlates of backward recall. Some functional magnetic resonance (fMRI) studies investigating forward and backward recall have identified areas involved in both processes, but differentially activated. For instance, Sun et al. (2005) identified higher activation of the occipital visual regions, and left prefrontal cortex (PFC) in backward recall of digits, supporting the involvement of visuospatial processing (Hoshi et al., 2000). In both processes inferior frontal gyrus and the central executive system were activated, with higher activations in backward recall (Sun et al., 2005; Carlesimo et al., 1994).

Alternatively, several studies have suggested the presence of different neural correlates for forward and backward recall (Manan et al., 2014). A fMRI study by Yang et al (2015) identified right dorsolateral PFC, the frontal eye field, the anterior insular cortex, and the dorsal anterior cingulate cortex (dACC). Interestingly, activation of the dACC was positively correlated with backward recall but negatively correlated with forward recall, supporting the separated neural correlates hypothesis.

The findings from imaging studies alone, although valuable for research, have not been very informative in terms of models for backward recall. This could partially be due to the separation of imaging studies from the theoretical models tested in behavioral studies. Our previous behavioral study has shown that the peel-off model is successful in modeling several aspects of backward recall performance, when chunking strategies are induced. The aim of this study is to use the previously used behavioral paradigm to gain a further understanding of backward recall neural correlates.

Methods

Participants and Exclusion Criteria

Twenty four right-handed volunteers (n=24; 12 female, 12 male; age range 19-35) will be recruited for the experiment in exchange for monetary compensation. The experimental procedures will be reviewed and approved by the local ethics committee at Western University, and written informed voluntary consent will be obtained before the experiment.

Participants will complete an Edinburgh Handedness Questionaire and only right-handed individuals will continue with the study. Left-handed individuals will be excluded since many cognitive functions have been shown to be lateralized, and the lateralization could be different between right-handed and left-handed individuals. Including only right-handed participants will limit between-subject noise. Lastly, individuals with a history of neurological disorders and/or more than six months of musical training will be excluded to limit noise in data.

Apparatus

An MRI-compatible custom-built keyboard will be used, such that numbers 1 to 4 corresponded to the right hand index finger, middle finger, ring finger, and pinky finger, respectively. Participants will face a LCD monitor with a [60Hz] refresh rate, where the task will displayed. PsychoPy software will be used to develop and display the experiment, as described in detail previously (Andersen et al., 2020; Peirce et al., 2019).

Task

Encoding Phase. We will use a six-digit span test, where participants are presented with 6 random digits (a string of numbers ranging from 1 to 4) within a number box at the centre of a black screen. The sequences of numbers will be presented in either chunks of 2 or 3 digits for 6 seconds in total. The chunking strategy within each trial will be assigned in a random order and remains consistent over the trial. To induce a specific chunking strategy (2 or 3-digits), the digits within each chunk will be presented simultaneously and closer together. Then the digits would turn to # symbols as the next chunk is presented. The participants do not receive any information about recall direction in the encoding phase to make sure that they make the encoding strategy consistent across trials.

Recall Phase. The 6 second encoding phase will be followed immediately by the recall phase, where participants are asked to recall the 6 digits from the encoding phase in either the forward or the backward direction. To cue the start of the recall phase, a colored square will appear to the left of the number box (Figure 2). A yellow square represents recall in the forward direction and a blue square represents recall in the backward direction.

Performance Feedback. Immediately following each press, participants will receive feedback by numbers they press turning red for wrong and green for correct answers.

At the end of the trial participants will receive points based on their accuracy within the trial for 0.5 seconds. Subjects receive 1 point for each accurate press and 10 points if all 6 digits are recalled correctly. At the end of each block of trials, a more detailed performance feedback will be displayed, including average accuracy, average trial time, and overall points. The overall points are calculated based on the accuracy and the average response time, such that accuracy points are doubled if average response time is under 8 seconds.

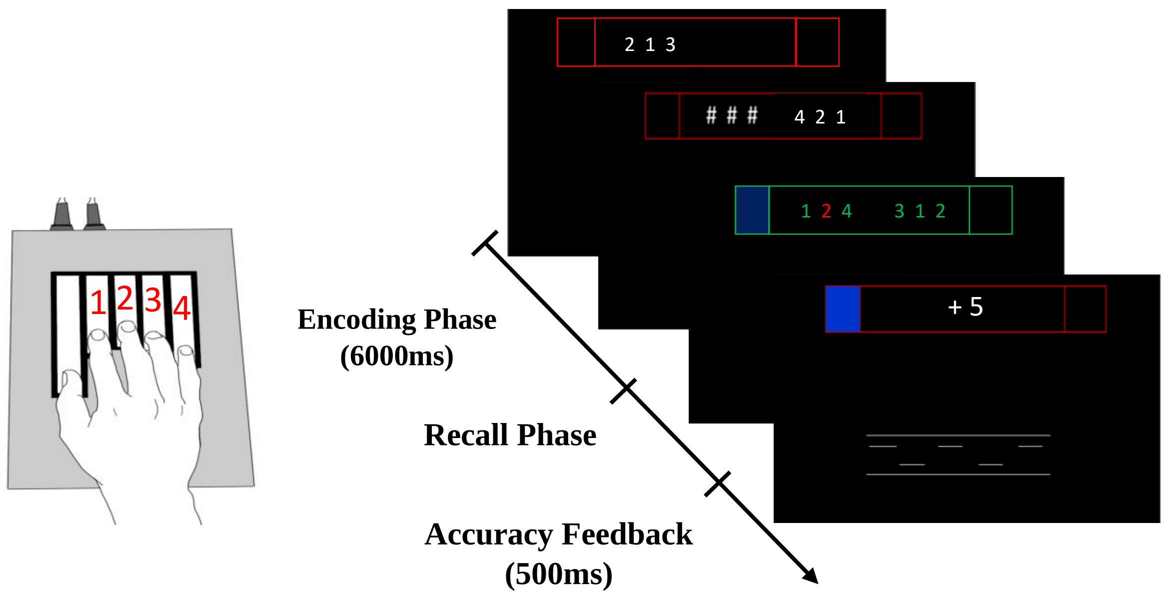

Figure 2. Immediate recall of digits task events over one trial. A: The MRI-compatible 4-finger keyboard used to recall digits with index finger on 1 and pinky finger on 4. **B:** Depicts the task progression during the experiment. In the 6-second encoding phase, the chunking strategy is induced, by presenting items one chunk at a time. The start of the recall phase is cued by the presentation of the colored box on the left: blue square for backward recall and yellow for forward. The recall direction does not appear in the encoding phase to ensure forward encoding direction. Lastly immediate feedback is provided based on accuracy throughout the trial.

Imaging Apparatus

This imaging will be performed using a MAGNETOM Siemens ultra-high field 7 Tesla scanner whole-body imaging MRI system at the Robarts Research Institute, using a Siemens radio-frequency 32-channel head coil to collect blood oxygen level dependent (BOLD) signal weighted images. T1-weighted anatomical images of the whole brain will be collected with axial slice orientation (TR = 1600 msec, voxel size = 1 mm × 1 mm × 1 mm). Functional T2*-weighted images of 32 slices will also be collected (slice thickness = 3 mm;TR = 2000 ms; 64 x 64 matrix size; FOV = 21 cm; voxel size = 3 mm x 3 mm x 3 mm).

Experimental Design

Behavioral Test. First participants will perfrom a behavioral test to ensure quality of data. To familiarize the subjects with the aparatus and the digit span task, all subjects will perform a block of 8 random balanced trials of the task. Participants will only received immediate feedback on their accuracy for each trial. This is followed by 8 experimental blocks of 12 random balanced trials each. The immediate performance feedbacks would be displayed after each trial, and a detailed feedbacks would be displayed at the end of each block. Participants will be verbally encouraged to perform as accurately and quickly as possible to achieve the highest overall points. Between each block there will be a 1-minute break, and participants are encouraged to take a 5 minute break at the half-way point. Only participants with overall accuracy greater than 85% will continue to the imaging test.

Imaging Test. During the imaging test, trials will be delivered using a rapid, jittered event-related design created with Optseq2. In each run there will be 6 trials for each condition (2 chunking condition × 2 recall direction). There will be an additional baseline condition, where participants are presented with 6 digits and have to immediately press the numbers they see, without any memorization. The baseline condition will be cued by the appearance of a white square to the left of the screen. This condition will control for activation in visual areas while participants are looking at the screen and motor areas when recruiting fingers. As the average movement time has been shown to be around 4000ms from the previous behavioral study, the experimental trials are estimated to last 10500 ms including the encoding phase and the immediate feedback phase. The baseline trials are estimated to last up to 4000ms. Overall, each run is estimated to last 276s (4 min and 36 sec), and the session will last 38 minutes, including breaks between runs.

Behavioral Analysis

A custom-written code in the Python 3.9.0 software will be used to analyze data behavioral data using publicly available libraries including Numpy, Pandas, Seaborn, and StatsModels. Only correct trials will be selected for further analyses. For each correct trial, we calculated movement time (MT, time between the first press and last release) and Interpress Intervals (IPIs, time between two consecutive presses). We will analyze the behavioral data using a 2×2 repeated measure analysis of variance (repeated measure ANOVA), and paired t tests. All t tests are two-sided unless specified otherwise. A probability threshold of $P < 0.05$ will used for the rejection of the null hypothesis in all statistical tests. To account for multiple comparisons, Bonferroni correction will be utilized.

Imaging Analysis

The fMRI Data will be analyzed using a Brain Voyager software package. Pre-processing will include scanning functional data for each participant for motion and magnet artifacts, and motions larger than 1mm within a run will be removed. The remaining data will be adjusted using Brain Voyager's motion correction. Moreover, a linear trend removal, a high-pass temporal filtering, and slice time correction will also be applied. Functional data will be superimposed onto anatomical images, alligned into Montreal Neurological Institute (MNI) space. First we will perform a voxel-wise analysis to identify activated areas in all four conditions. Then we will specificially look into the PFC, the occipital visual regions, the frontal eye field, the anterior insular cortex, and the dorsal anterior cingulate cortex (dACC), based on anatomical coordinates in the MNI space and Mindboggle atlas. We will then use a general linear model with four predictors for each of the conditions. Predictors are generated using rectangular wave function that are convolved with a 2-gamma factor hemodynamic response function (Boynton et al., 1996). The raw data will be transformed to percent signal change (%BSC), and activation in each condition will be compared to the baseline condition. To account for multiple comparisons a False Discovery Rate (FDR) threshold of $q < .05$ will be used, followed by the removal of small clusters (< 90 mm^3). A gray matter mask, which excluds voxels from outside of the brain, voxels in large white matter regions, and voxels from inside ventricles, will also be applied. The beta weights collected from the data in the four condition will be subject to a 2 recall direction by 2 chunking level analyses of variance (ANOVA).

Hypothesized Results and Discussion

We expect to see similar behavioral results as our previous study. Specifically, we expect to see backward recall occurring with lower accuracy and slower than forward recall in both chunking conditions. Moreover, we expect to see lower accuracy and slower movement times during the 2-digit chunking conditions compared to 3-digit chunking. Lastly, we will examine the inter-press intervals and expect to see patterns similar to those predicted by the peel-off model.

The peel-off model predicts that the backward recall is actually performed by a series of forward recalls, that is only different from forward recall by the peel-off operations performed. The additional peel-off steps are visuspatial processes, thus, we would expect to see higher activation in the viual regions and the PFC during backward recall (Figure 3). Similar activation patterns are expected in the frontal eye field and the anterior insular cortex (Figure 3). Moreover, since these operations are the only steps seperating forward and backward recall, the difference in activation level might be correlated with the number of items peeled-off. There could also be areas activated only by the backward recall, possibly representing the peel-off steps. Based on previous findings we would only expect to see activation of dACC during backward recall (Figure 4). Alternatively, we could find equal activation in both recall directions in PFC, visual regions, and anterior insular cortex (Figure 3). This would mean that these areas are not involved in the peel-off step and other areas like the dACC carry out the peel-off step.

Regarding chunking strategies, there could be differences between the two chunking levels. Earlier studies and results from our previous study suggest that larger chunks improve recall performance better than smaller chunks. This could reflect the cognitive load on the brain while processing chunks of information is lower when larger chunks are processed due to fewer number of chunks. Thus, we would predict to see higher activation in the 2-digit chunking condition due to working memory being more taxed. Brain regions implicated would likely be similar to areas mentioned for recall direction and would include the PFC, visual regions, anterior insular cortex, and frontal eye field. We also hypothesize that there would not be any interactions between recall direction and chunking strategy, since we did not find an interaction in the previous behavioral study.

In this study we tried to understand the neural implementation of the peel-off model for backward recall in working memory. Understanding the mechanism underlying working memory could shed light on potential ways to enhance memory in patient populations and the elderly. As backward recall has been used to reliably measure executive function and has been strongly linked to age-related cognitive decline (Bopp & Verhaeghen, 2005), it is important to study its mechanism. If the Peel-off model accurately represents how the order reversal occurs in working memory, we could try to understand the activation patterns in the brain in the light of this model. If the findings of this study do support the peel-off model, future studies should focus on activation patterns elicited by each step of the recall operations. Alternatively, if there are no differences between activation patterns and intensities between forward and backward recall, this could suggest that the brain can recall items with equal facility in both directions (Norris et al., 2019), which goes against the peel-off model.

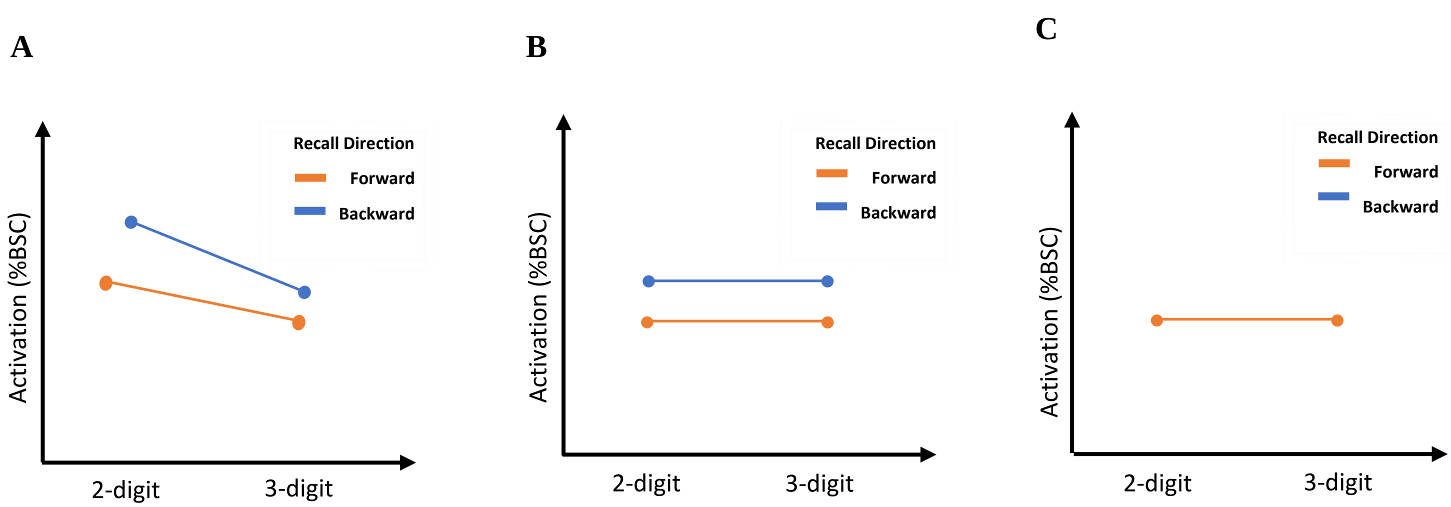

Figure 3. Alternative hypotheses for activation patterns in the 2 Chunking X 2 Recall direction design in PFC and visual regions A: Hypothesis that there will be a main effect of chunking, main effect of recall direction and an interaction, where chunking strategy effects both backward and forward recall. **B:** Hypothesis that there will be a main effect of recall direction only, where the activation lines would be parallel and backward recall results in higher activation. **C:** Hypothesis that there will not be a main effect of chunking, no main effect of recall direction and no interaction, where activation does not change. This is not predicted

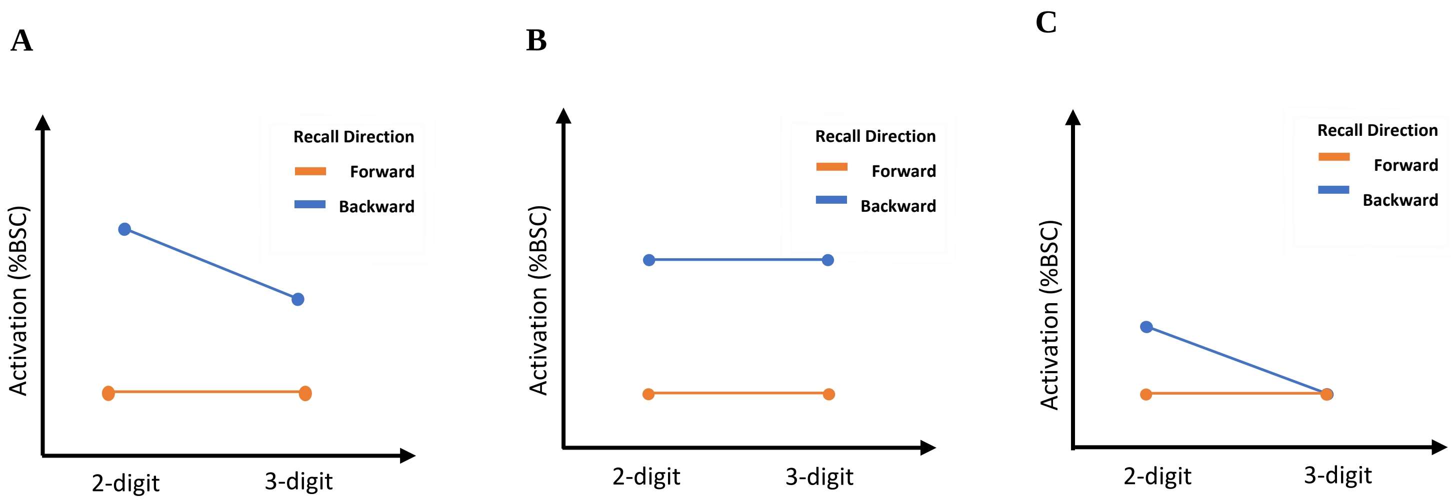

Figure 4. Alternative hypotheses for activation patterns in the 2 Chunking X 2 Recall direction design in dACC A: Hypothesis that there will be no activation in forward recall, a main effect of chunking, a main effect of recall direction and an interaction, where chunking strategy only effects backward recall. **B:** Hypothesis that there will be no activation in forward recall and a main effect of recall direction, where the activation lines would be parallel and backward recall only results in activation. **C:** Hypothesis that there will be no activation in forward recall, a main effect of chunking, a main effect of recall direction, and an interaction, where chunking strategy effects only the backward recall.

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