The role of working memory in spatial enumeration: Patterns of selective interference in subitizing and counting

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Articulatory suppression (repeatedly pronouncing a syllable or word while carrying out another task) is thought to interfere selectively with the phonological store in working memory (Larsen & Baddeley, 2003). Although suppression interferes with temporal enumeration (enumerating successive light flashes), to date there has been little evidence of such interference in spatial enumeration (enumerating units laid out in space at one time)—a finding with serious ramifications for theories of enumeration. Participants carried out a spatial enumeration task, enumerating 1–8 dots while listening to a metronome (baseline condition) or while carrying out a secondary task to the rhythm of the metronome (dual-task condition). There were four secondary tasks: simple articulation (saying a letter), complex articulation (alternating between two letters), simple tapping (tapping a finger), and complex tapping (alternating between two fingers). Interference varied with number of items, but the pattern differed from that observed with temporal enumeration (Logie & Baddeley, 1987).

This study is about spatial enumeration: enumeration of units that are all present at one time in different spatial locations. For example, determining the number of dots in a visual display involves spatial enumeration. The converse of spatial enumeration is temporal enumeration: enumeration of units that are defined by changes that occur over time at one spatial location. Determining the number of times a light flashes in the center of a visual display involves temporal enumeration. In this article, I argue that there are differences between spatial and temporal enumeration that reveal interesting differences in the processes involved in constructing and individuating the basic building blocks of conscious experience: objects and events. These differences reveal themselves in variations in working memory use.

This investigation is relevant to research on working memory, insofar as it builds on the findings of a classic and much cited paper in that literature (Logie & Baddeley, 1987). However, this research is of particular importance to the study of enumeration. There are many theories of enumeration, but one assumption has haunted the literature since its outset: the assumption that because all forms of enumeration involve making a numeric response, all forms of enumeration work in the same way, making use of the same operations and producing the same patterns of performance. A modern manifestation of this idea

can be found in Wynn (1996, p. 164), who argued that the ability to enumerate punctate tones is evidence against perceptual theories that endeavor to explain performance in visual-spatial enumeration. This assumption is also implicit in studies in which direct inferences about the nature of number representation have been made on the basis of performance in one particular enumeration task, without replicating the results with different types of enumeration tasks in order to ensure that the findings were not dependent on factors related to the defining and individuating of specific types of units (e.g., Cordes, Gelman, Gallistel, & Whalen, 2001).

There has never been a real test of the assumption that spatial and temporal enumeration work in the same way, partly because the two forms of enumeration require different dependent measures. Spatial enumeration studies focus on response time (RT) because error rates are low and floor effects make error data difficult to interpret. Temporal enumeration studies analyze error rates, because events unfold over time and measurements of RT are impossible when it is unclear when timing should start. Direct comparisons of spatial and temporal enumeration are difficult within the visual modality, let alone comparisons between vision and hearing. However, it might be possible to challenge the assumption that the two types of enumeration work in the same way if it were possible to demonstrate that spatial and temporal enumeration exhibit different patterns of working memory use.

Recent investigations suggest that there are several types of working memory: a phonological loop designed for operations involving language and speech sounds, a spatial sketchpad specialized for visual and/or spatial operations, and a central executive, responsible for coordinating and sequencing the activity of the phonological

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and the spatial systems (Baddeley & Logie, 1999). Articulatory suppression, a secondary task that involves repeatedly articulating a syllable or word (e.g., saying “the the the”), is thought to interfere selectively with the phonological loop, leaving other forms of memory unaffected (e.g., Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002). Therefore, one way to gauge how much spatial or temporal enumeration uses phonological working memory is to measure interference—that is, to measure how much worse performance is when participants enumerate while articulating sounds (dual-task condition) than when enumerating in isolation (baseline condition).

Logie and Baddeley (1987) have conducted the only investigation of articulatory suppression as it affects spatial and temporal enumeration. The effects of articulatory suppression were compared with those of manual tapping, an attentional control that was not expected to interfere with phonological memory. One study involved visual/spatial enumeration: Participants enumerated dots. The other four involved visual/temporal enumeration: Participants enumerated flashes of light that appeared at unequal intervals in the center of the screen. The researchers predicted that articulatory suppression would interfere more than tapping in both types of enumeration, but their results did not fully support this expectation. In fact, neither secondary task appears to interfere appreciably until there are more than 7 dots. In contrast, when participants enumerated flashes of light, articulatory suppression produced significantly more interference than did tapping throughout the number range from 1 to 25 (as indicated by increased error rates in the dual-task condition).

The researchers did not pursue the discrepancies between spatial and temporal enumeration. However, from the perspective of enumeration theory, these results are ambiguous and problematic. They might show that the two types of enumeration exhibit different patterns of memory use. They might also indicate that the spatial enumeration methodology was insufficiently sensitive to pick up interference effects in RT.

The goal of the present study is to resolve this ambiguity by dealing with factors that may have obscured interference effects in Logie and Baddeley’s (1987) dot enumeration study. First, given that spatial enumeration takes place so quickly, it is possible that the participants slowed down or stopped performing the secondary task while enumerating. To ensure a consistent response rate, in the present study, the participants articulated or tapped to the beat of a metronome (a sound that should not interfere; Tremblay & Jones, 1998).

Second, it is possible that articulatory suppression had varying effects, depending on the number of items, and that this disguised overall differences between articulation and tapping. It has long been known that there are differences between enumerating small and large numbers of dots (e.g., Jevons, 1871). When there are small numbers (1–3 or 1–4 for most adults), enumeration is effortless, immediate, and accurate, and enumeration time

increases minimally with each additional dot (slope = 40–120 msec/item). This type of enumeration has been called *subitizing*; the *subitizing range* is the range of numbers in which this type of enumeration occurs. When there are more than 4 or 5, enumeration is effortful and error prone, and each additional dot adds substantially to RT (slope = 200–350 msec/item). This type of enumeration has been called *counting*. Trend analysis can be used as an index of whether subitizing or counting occurs because it registers the increase in RT slope as a deviation from linearity.

Trend analyses were not performed in Logie and Baddeley’s (1987) studies. There are several reasons why these analyses should be done. Manipulations that force focused spatial attention eliminate subitizing, making the enumeration RT slope constant and high throughout the number range (Trick & Pylyshyn, 1994). It is important to ensure that secondary tasks do not produce similar effects. As well, some maintain that subitizing reflects capacity limitations in working memory (e.g., Cowan, 2001; Klahr & Wallace, 1976). Given that articulatory suppression is thought to interfere with the storage and rehearsal of information in phonological working memory (Larsen & Baddeley, 2003), it is possible that articulatory suppression might eliminate subitizing. Moreover, trend analysis would permit comparisons between the subitizing and the counting ranges. This would help resolve a longstanding dispute in the enumeration literature between those who believe that subitizing and counting are manifestations of the same process applied to different numbers of items (e.g., Balakrishnan & Ashby, 1992) and those who believe that subitizing and counting are separate processes (e.g., Klahr & Wallace, 1976; Trick & Pylyshyn, 1994). If patterns of interference differ in the subitizing and counting ranges, this would support the idea that subitizing and counting involve different processes.

Third, it is possible that effects did not emerge in spatial enumeration because the secondary task was too easy in Logie and Baddeley (1987). In the present study, the complexity of the secondary task was manipulated by increasing the number of tokens to be repeated from one to two (e.g., Larsen & Baddeley, 2003). There were four secondary tasks: simple articulation (repeating a single letter), complex articulation (alternating between two letters), simple tapping (tapping a single finger), and complex tapping (alternating between two fingers). This manipulation is interesting, given that tasks that involve switching responses might be expected to put demands on the executive component of working memory, which is used to sequence activities. As well, some have found that increasing the number of tokens augments the articulatory suppression effect (e.g., Macken & Jones, 1995), although to date, no one has shown the same for tapping (Baddeley & Larsen, 2003).

Enumeration RT and error rates were measured as a function of four independent variables: secondary task modality (articulation or tapping), secondary task complexity (simple or complex), condition (baseline or dual

task), and number of items (1–8). To avoid transfer between different secondary tasks, task modality and complexity were run as between-subjects manipulations.

On the basis of Trick and Pylyshyn's (1994) account of visual/spatial enumeration, subitizing and counting should be apparent in all conditions, but the pattern of interference should differ from that shown in temporal enumeration and should vary on the basis of the number of items. Modality and complexity should have stronger effects in the counting range than in the subitizing range, because the counting process makes greater use of the phonological loop and the executive.

METHOD

Participants

Students from the university participant pool were randomly assigned to one of the following secondary tasks: simple articulate "F" ($n = 18$), simple articulate "S" ($n = 18$), complex articulate ($n = 28$), simple tap ($n = 21$), and complex tap ($n = 27$). The articulate "F" and "S" groups were combined to form a simple articulate group ($F < 1$ between groups for both RT and error).

Apparatus and Stimuli

The participants were seated 60 cm from a Macintosh G4 computer. Each trial involved a series of displays. The first involved a centered 0.5° fixation cross. The second had either the word *READY* (baseline condition) or *START* (dual-task condition). The enumeration display came next, featuring 1–9 randomly positioned 0.28° black dots on a white background (8.6° × 8.6° area). The final display was a mask made up of black dots in all the possible item locations.

A Qwik Time metronome set to tick at 90 beats per minute was used to help the participants pace their secondary task response rate. A button box was also used (1.5-cm-round keys; 2 cm between keys, measured center to center).

Procedure

The participants were seated in front of a computer monitor with the right index finger poised on the space bar of the keyboard. The button box was stationed to the left of the keyboard within easy reach, and the participants in the tapping condition kept their fingers positioned over the keys on the box. The metronome ticked for the duration of the experiment.

Each participant enumerated dots while the metronome ticked (baseline condition) or while performing a secondary task to the beat of the metronome (dual-task condition). The participants in the simple articulate task repeated the same letter every time the metronome ticked (letter "F" for some subjects and letter "S" for others), and those in the complex articulate task alternated between two letters ("FS"). The participants assigned to the simple tap task tapped a button on the button box with the left index finger every time the metronome ticked; those assigned to the complex tap task alternated between tapping the left index and the middle fingers.

Each trial began with a 60-msec fixation cross, followed by a 20-msec blank interval. In the baseline condition, the word *READY* appeared on the computer screen and remained for 1,111 msec, followed by a 20-msec blank and the dot display. In the dual-task condition, the word *START* appeared for 1,111 msec, followed by a 20-msec blank and the dot display. The participants began their designated secondary task as soon as they saw the word *START*. In both conditions, the dot display terminated as soon as the participants hit the space bar to indicate that they knew the number of dots. The pattern mask appeared, and the participants typed in the number. (If the typed number did not correspond to the number of dots,

the trial was scored as an error.) The next trial began once the participants had repositioned their hands over the space bar and, in the tapping conditions, the button box.

Half of the participants started with the baseline, and half started with the dual-task condition. Training was given immediately before the relevant condition. The participants were taught the enumeration task, and in the dual-task conditions, they were first given practice on their designated secondary task in isolation before they graduated to performing it while enumerating. After training, the participants were given 27 practice trials. There were a total of 270 experimental trials, five blocks of 27 in the baseline and dual-task conditions. A research assistant monitored the participants throughout testing and ensured that they tapped or articulated to the beat of the metronome.

RESULTS

Raw Data

Enumeration latencies and error rates were analyzed to determine that the two within-subjects factors (number and condition) had the expected effects and to establish that there were no differences in baseline performance between the groups assigned different secondary tasks. RTs were further analyzed to determine whether the deviation from linearity indicative of subitizing and counting occurred. Although the participants enumerated 1–9 dots, the data from trials with 9 dots were not analyzed, because of end-of-range effects, which are typical in enumeration studies (e.g., Mandler & Shebo, 1982). End-of-range effects occur when participants begin to guess the largest number in the range whenever there are a large number of items.

Enumeration RT. Error trial latencies were dropped from the analyses. RTs were trimmed so that for each participant, for each number, and for each condition, only latencies that fell within two standard deviation lengths of the mean for that particular individual at that number and condition were included. Fewer than 5% of the trials were lost to trimming. All the effects were replicated when a three standard deviation trimming criterion was used.

RTs increased with the number of items [number, $F(7,756) = 1,364.1$, $MS_e = 63,785$, $p < .001$] and was higher in the dual-task condition [condition, $F(1,108) = 26.2$, $MS_e = 103,818$, $p < .001$], as is shown in Figure 1. For each of the four secondary tasks, baseline and dual-task performance was compared. All but the simple articulate group showed dual-task interference [simple articulate, $F < 1$; complex articulate, $F(1,27) = 11.9$, $MS_e = 79,740$, $p < .005$; simple tap, $F(1,20) = 7.9$, $MS_e = 69,600$, $p < .05$; complex tap, $F(1,26) = 10.0$, $MS_e = 205,030$, $p < .005$]. There were no significant differences between groups in baseline performance ($F < 1$).

Subitizing and counting were evident in all the conditions and tasks, with small increases in enumeration time per item up to 3 or 4 items and larger increases thereafter. Trend analyses measuring the effect of numerosity on RT were performed for each of the four secondary tasks for both the baseline and the dual-task conditions (a total of eight analyses). Significant quadratic trends emerged once there were 1–4 items in all analyses ($p <$

Figure 1. Mean correct enumeration reaction time (RT) for individuals enumerating while carrying out a secondary task (dual-task condition) or for the same individuals enumerating in isolation (baseline condition). Figures 1A–1D represent data from simple articulation, complex articulation, simple tapping, and complex tapping tasks, respectively.

.05 for all). Consequently, the subitizing range was considered to be 1–3 for this study.

Enumeration error rates. The error rate was low overall ($M = 3.4\%$) but increased with the number of items [number, $F(7,756) = 54.6$, $MS_e = 42$, $p < .001$], as is shown in Figure 2. The participants made more errors in the dual-task condition [condition, $F(1,108) = 44.1$, $MS_e = 54$, $p < .001$], and there was a condition $\times$ number interaction, indicating that the participants were especially error prone when enumerating large numbers of items while performing secondary tasks [$F(7,756) = 12.6$, $MS_e = 25$, $p < .001$]. There were more errors in the dual-task than in the baseline condition for all four tasks, although the effect was only marginal for the simple tap group [simple articulate, $F(1,35) = 10.5$, $MS_e = 41$, $p < .005$; complex articulate, $F(1,27) = 22.9$, $MS_e = 77$, $p < .001$; simple tap, $F(1,20) = 3.3$, $MS_e = 55$, $p = .086$; complex tap, $F(1,26) = 11.7$, $MS_e = 44$, $p < .005$]. There were no differences between groups in baseline error rates ($F < 1$).

Interference Scores

To ensure that the differences between tasks were not the result of differences in baseline performance, comparisons between secondary tasks were made, using interference scores. Interference was calculated by subtracting

baseline from dual-task performance (see Figure 3). Analyses began with a consideration of the full number range (1–8). If interactions involving number occurred, separate analyses were carried out in the subitizing and counting ranges (1–3 and 6–8 items, respectively) because subitizing and counting are thought to involve different processes. Latencies for 4 and 5 items were not analyzed, to avoid mixing data from the participants who were using different enumeration processes; some adults can subitize as many as 5 items (see, e.g., Trick & Pylyshyn, 1994).

RT interference. There was a number $\times$ modality interaction and a marginal main effect of modality [number $\times$ modality, $F(7,756) = 2.2$, $MS_e = 33,739$, $p < .05$; modality, $F(1,108) = 3.8$, $MS_e = 207,636$, $p = .054$]. However, the form of the interaction was unanticipated, because tapping produced more interference than did articulation. There was also a main effect of complexity [$F(1,108) = 5.3$, $MS_e = 207,636$, $p < .05$], but the predicted interaction between number and complexity was not significant [$F(7,756) = 1.6$, $MS_e = 33,739$, $p > .1$]. No other effects emerged ($F < 1$ for all).

When the subitizing and the counting ranges were analyzed separately, there were no further interactions involving number, which suggests that the pattern of interference was roughly consistent within each range. Secondary task modality had a significant effect on RT

Figure 2. Mean enumeration error rates for individuals enumerating while carrying out a secondary task (dual-task condition) or for the same individuals enumerating in isolation (baseline condition). Figures 2A–2D represent data from simple articulation, complex articulation, simple tapping, and complex tapping tasks, respectively.

interference when the participants enumerated 1–3 items. Tapping tasks produced 99 msec more interference than did articulation tasks [134 msec, as compared with 35 msec, on average; modality, $F(1,108) = 28.4$, $MS_e = 27,923$, $p < .001$]. Secondary tasks that involved alternating responses produced 56 msec more interference than did those that did not [113 msec, as compared with 57 msec; complexity, $F(1,108) = 9.2$, $MS_e = 27,923$, $p < .05$]. There were no other significant effects ($F < 1$ for all).

In contrast, when there were 6–8 items, tapping produced only 11 msec more interference than did articulation (95 msec, as compared with 84 msec; modality, $F < 1$). Complex tasks produced 111 msec more interference than did simple tasks [145 msec as compared with 34 msec; complexity, $F(1,108) = 3.7$, $MS_e = 269,031$, $p = .056$]. The complexity effect was about twice as large in the counting range as in the subitizing range (111 msec, as compared with 56 msec) although the number $\times$ complexity interaction was not significant when the full 1–8 range was analyzed. No other effects emerged ($p > .05$ for all).

Error interference. The amount of error interference was low ($M = 2.3\%$), but there were several significant effects [number, $F(7,756) = 12.6$, $p < .001$; number $\times$ complexity, $F(7,756) = 3.4$, $p < .01$; number $\times$ modal-

ity, $F(7,756) = 3.4$, $p < .01$; $MS_e = 51$ for all; complexity, $F(1,108) = 4.4$, $MS_e = 107$, $p < .05$].

None of the factors had significant effects on error interference in the 1- to 3-item range ($F < 1$); mean error interference was less than 1% for every task. However, in the 6- to 8-item range, there was a main effect of complexity [$F(1,108) = 4.9$, $MS_e = 186$, $p < .05$] and several interactions [number $\times$ modality, $F(2,216) = 4.8$, $p < .05$; number $\times$ complexity, $F(2,216) = 4.5$, $p < .05$; $MS_e = 83$ for both]. When there were 6–8 dots, error interference increased with the number of items, particularly when the tasks involved articulation or alternating between responses.

DISCUSSION

This research is primarily about enumeration, and for purposes of the enumeration literature, there are three principal findings.

1. The pattern of interference with spatial enumeration was different from that which has been observed with temporal enumeration. For example, in the 1- to 3-item range, tapping tasks produced more interference than did articulation tasks, exactly the opposite pattern to that shown in temporal enumeration (Logie & Baddeley, 1987). These results suggest that spatial enumeration makes

Figure 3. Mean interference (dual-task – baseline performance) as a function of the number of items to be enumerated and the modality and complexity of the secondary task. Figure 3A represents reaction time (RT) interference measured in milliseconds (dual-task – baseline RTs), and Figure 3B represents error interference (dual task – baseline error rate percentages).

fewer demands on phonological working memory. This makes sense, given the requirements of each task. In temporal enumeration, items are presented one at a time; there is no way to reverse time to review the display. Either there would have to be a detailed memorial record of the sequence of events that could be “replayed,” or the units would have to be defined, individuated, and assigned number names immediately, as they were presented (i.e., each number name would have to be represented in turn, and each name would have to be maintained in phonological memory until the next unit appeared). In spatial enumeration, all items are presented simultaneously. Consequently, it is possible that several items might be defined and individuated at once. If information about individuated items could be used to access a number representation from long-term memory, this would mean that working memory demands could be restricted to those necessary for accessing a single number name (the number corresponding to the total). That is what occurs during subitizing. If there proved to be too

many items to enumerate at a glance, spatial displays could be revisited. In this case, accurate enumeration would require working memory representations of the number previously viewed, as well as the number currently being enumerated (for purposes of mental addition). That is why articulation interferes more in the counting range and why interference increases with the number of items.

2. Subitizing and counting occurred in all the conditions and for all the tasks, as shown by deviations from linearity in the trend analysis. This suggests that the emergence of subitizing and counting is unaffected by manipulations designed to compromise storage and rehearsal in phonological working memory.

3. The pattern of interference varied with the number of items. In the 1- to 3-item range, tapping tasks produced significantly more interference than did articulation tasks. In the 6- to 8-item range, tapping and articulation tasks produced about the same amount of RT interference, but there was more error interference for articulation

tasks. These dissociations suggest that different processes are involved in subitizing and counting, with phonological memory playing a larger role in counting.

The results also have interesting implications for working memory. There was one new finding: Increasing the number of tokens increased the amount of interference produced by both articulation and tapping (by $M = 86$ and 57 msec, respectively). This study is the first that shows that increasing the number of tokens can affect the amount of interference produced by tapping. There was also a surprise: Simple articulation did not interfere appreciably with spatial enumeration, but simple tapping did [M RT interference = 6 and 81 msec, respectively, $F(1,55) = 6.0$, $MS_e = 135,585$, $p < .05$; M error interference = 1.7% and 1.5% , respectively, $F < 1$].

It is difficult to explain why tapping interfered so much. Although there have been studies that have shown that syncopated tapping can produce as much interference as articulatory suppression (Larsen & Baddeley, 2003; Saito, 1993, 1994), tapping interfered more than articulation in this study. Perhaps the results reflect interference in visual/spatial working memory. It is certainly plausible that visual/spatial enumeration employs visual/spatial working memory, and some forms of manual response have been shown to interfere with the sketchpad (e.g., Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999). However, manual responses that produce this kind of interference involve spatial uncertainty and require participants to hold item positions in memory. In this study, there was no spatial uncertainty or need to remember spatial locations; the participants had their fingers resting on the keys. Alternatively, there may have been more than normal amounts of interference between tapping and the timed manual enumeration response in this study because the responses were more similar to one another. Both involved fingerpresses.

Nonetheless, overall, the results challenge the idea that all forms of enumeration take place in the same way. Although all forms of enumeration require making a numeric response, unit definition and individuation processes may necessarily vary between tasks (Wagner & Carey, 2003). At this point, it is not even clear that subitizing occurs in all forms of enumeration, and in some cases, it will be difficult to show that it does, given that RT slope is the prime indicator. There may be parallels between different types of enumeration, but ultimately, they may produce different patterns of performance that need to be explained in different ways.

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