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## Examining the role of working memory resources in following spoken instructions

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### Abstract

This study investigated the involvement of working memory in following spoken instructions using concurrent tasks designed to disrupt components of the Baddeley and Hitch working memory model (1974). In each of three experiments, participants were presented with sequences of instructions to be either verbally repeated or physically performed using relevant objects. Backward counting, articulatory suppression and eye closure during instruction encoding all disrupted recall, and also impaired recall of the linkage between movements and objects. Recall of actions was more accurate when they were physically enacted than repeated verbally, an advantage that was not affected by concurrent tasks. These findings indicate that aspects of the recall of spoken instructions including the binding of constituent movements to objects draw on multiple working memory resources. The benefits of physical enactment of the instructed sequence do not appear to depend on the components of working memory investigated in these studies.

*Keywords:* Working memory, Following instructions, Enactment benefit

Word count (main text):6333

Performing actions to command such as following a new recipe, remembering an instructor's guidance when learning to drive, or following a teacher's instructions are common experiences in everyday life. Each of these situations requires remembering a series of action steps in sequence and performing them shortly after. Instructions typically need either to be comprehended and maintained before they can be executed, or to be maintained in verbatim form for later comprehension. These task demands are likely to involve working memory (WM), a limited capacity system that enables us to temporarily hold information in mind and manipulate it as necessary.

The close relationship between WM and following instructions has been demonstrated in several studies (Brenner, 1940; Engle, Carullo, & Collins, 1991; Gathercole, Durling, Evans, Jeffcock, & Stone, 2008; Kaplan & White, 1980; Kim, Bayles, & Beeson, 2008). In an early investigation (Brenner, 1940), participants were given simple commands such as "put a comma below B". The ability to follow instructions was significantly correlated with digit span, a measure of short-term memory. The Token Test was later developed for aphasic patients, involving carrying out instructions such as "after picking up the green rectangle, touch the white circle" (De Renzi & Vignolo, 1962). While this task was initially developed to detect impairment in grammatical processing, performance has also been found to significantly correlate with verbal, visual, and motor aspects of short-term memory (Lesser, 1976).

Later studies have examined instruction following by children in the classroom (Engle et al., 1991; Kaplan & White, 1980) and here too, links have been found with WM abilities. Gathercole and Alloway (2008) observed that children who score poorly on central executive measures (i.e. the ability to manipulate information) have marked difficulties in carrying out instructions within the classroom. An

instruction task was designed to investigate this issue (Gathercole et al., 2008), with instructional sequences varying only in length of steps, while grammatical complexity was held constant to exclude any language development confounds. Five-year-old children listened to instructions (e.g. “*touch the red pencil, then pick up the blue ruler and put it in the black box*”) and were required to recall either by verbally repeating the instruction sentence or physically enacting it on relevant objects. Children were more accurate in performing the instruction than verbally repeating them. The accuracy of performing (although not repeating) instructions was associated with measures of storage in WM such as digit span and, even more strongly, with complex span measures imposing storage and processing demands such as backward digit recall.

More detailed investigation of WM involvement in following instructions was conducted by Yang, Gathercole, and Allen (2014), guided by the WM model of Baddeley and Hitch (Baddeley, 1986; Baddeley & Hitch, 1974). According to this model, WM consists of a temporary store for phonological information involving obligatory storage for auditory information and intentional rehearsal, and another store for visuospatial information. These are supplemented by an attentional system, the central executive, that regulates storage and is assumed to have a range of executive functions, such as switching between tasks, updating, inhibiting, as well as controlling attention (Baddeley, 1996, 2007). Yang et al. (2014) examined performance of young adult participants using a dual task approach to selectively disrupt WM components during encoding of written instructions. All interference tasks were performed during the presentation of instructions, prior to recall. Recall was substantially disrupted by all concurrent tasks (articulatory suppression, spatial tapping, and backward counting), suggesting that multiple components of WM are

required for encoding and retaining written instructions. While accuracy of recalling the instructions was higher when they were recalled by enactment than orally repeated (as in Gathercole et al., 2008), the advantage was unaffected by concurrent tasks, indicating that it does not cost additional WM resources. These findings therefore establish a significant role for multiple WM components in remembering written forms of instructions, although not to a greater extent for their enactment, relative to simple verbal repetition.

Guided by the view that WM is a flexible limited resource that allows allocation of memory resource to prioritized items in memory depending on the task requirement (Hu, Hitch, Baddeley, Zhang, & Allen, 2014; Ma, Husain, & Bays, 2014), the present research examines whether these WM components are also engaged in remembering and performing spoken instructions, an activity that is commonly experienced from infancy onwards. Spoken instructions differ from written instructions in several ways. First, spoken instructions gain direct access to the phonological store (Baddeley, Lewis, & Vallar, 1984) while visually presented information relies on the rehearsal process for phonological recoding (Baddeley & Larsen, 2007; Vallar & Papagno, 2002) and the integration of information by phonological loop during reading (Rayner, 1998). Second, the visuospatial sketchpad may make a greater contribution to the performance of written instructions by retaining visual forms of words in addition, possibly. Regardless of the input modality, it may also be involved in maintaining of visuo-spatial representations of the objects to be manipulated. Third, encoding written instructions may involve dividing attention between viewing the text and the objects in the display, whereas spoken instructions can be mapped onto a visuo-spatial representation of actions simultaneously. The key

cognitive mechanisms involved in following spoken and written instructions may therefore differ.

This article reports three experiments that use the dual-task WM methodology to explore WM involvement in following spoken instructions. Participants heard spoken instructions involving the manipulation of sequences of objects such as “pick up the red pencil then put it into the black box” which they then either recalled verbally or performed on an array of objects (Gathercole et al., 2008). In Experiment 1, articulatory suppression and backward counting concurrent tasks were employed to disrupt the phonological loop and central executive, respectively (Allen, Baddeley, & Hitch, 2006; Murray, 1968; Postma & De Haan, 1996). The role of the visuospatial sketchpad was investigated in Experiment 2 using a spatial tapping task adapted from Smyth et al. (1988). In Experiment 3, participants either kept their eyes open or closed as the instructions were being presented in order, in the latter condition, to disrupt the potential use of visualisation to guide encoding of the instructions. In all three experiments, the potential role of working memory in binding movements to objects within an action chunk was also investigated, for the first time. Binding different elements into an integrated representation is assumed to be the role of the episodic buffer, a temporary modality-general store that binds information within working memory and also from long-term memory and perceptual channels into a coherent episode, with a capacity potentially limited by the number of chunks or episodes that can be simultaneously retained (Baddeley, 2000; Baddeley, Allen, & Hitch, 2010, 2011). Examining how binding between elements is impacted by different encoding manipulations, and how they are retrieved for verbal or enacted recall, will provide new insights into the ability to follow instructions specifically, and working memory functioning in general. In addition to implications for theory, an increased

understanding of the cognitive processes involved in supporting the ability to follow, recall, and implement instructions will usefully feed into the development of techniques and interventions designed to support healthy and disordered individuals across a variety of educational, training, and clinical settings.

### Experiment 1

This experiment investigated the extent to which immediate memory for spoken instructions depends on the phonological loop and central executive components of working memory. Recall of the physical instruction sequence was either verbal or performed, and was accompanied either by articulatory suppression (disrupting the phonological loop, Baddeley, Thomson, & Buchanan, 1975), backwards counting (disrupting the loop and the central executive due to the additional processing load, Allen et al., 2006) or no concurrent task. Comparison of the two recall modalities allowed us to examine whether the enactment benefit over verbal repetition found with spoken instructions in children (Gathercole et al., 2008) and in adults with written instructions (Yang et al., 2014) also extend to written instructions in young adults.

The experiment tested the following hypotheses. First, if the phonological loop serves the storage and rehearsal of the verbal instructions (Baddeley, 2007; Baddeley, Hitch, & Allen, 2009), articulatory suppression should impair recall. Second, as the central executive provides attentional control within WM (Baddeley, 1996, 2007), it may also be important for the planning and execution of actions such as encoding spoken commands by paying selective attention to intended objects, linking movements with target objects, and keeping track of completion status of actions. On this basis, as well as the close links between backward digit span and following spoken instructions already reported by Gathercole et al (2008) and a disruptive



impact on backward counting on following with written instructions by Yang et al. (2014), concurrent backward counting task was predicted to impair performance. Third, on the basis of previous findings, recall by actions was expected to be superior to simple verbal repetition (Gathercole et al., 2008; Yang et al., 2014) under all concurrent task conditions. Finally, on the basis of the broader proposal that the episodic buffer plays a role in binding multi-modal representations (Baddeley, 2010; Baddeley et al., 2010, 2011), accuracy of linkage between movements and specific objects was examined. While research has indicated that binding within visual or verbal working memory might not specifically require general attentional support beyond that required for the individual features (e.g. Baddeley et al., 2011), this might not extend across all contexts; binding between each movement and object within a multi-item sequence might critically draw on executive support, in line with the original conception of the episodic buffer (Baddeley, 2000). In this case, we would expect that memory for binding within movement-object pairs to be particularly disrupted by backward counting.

### *Method*

#### *Participants*

Twenty-four native English speakers (aged 18 to 26 years), all students at the University of York, attended the experiment in exchange for course credit or an honorarium.

#### *Materials*

The three-dimensional task environment involved colorful stationary objects, including six small items (yellow ruler, blue ruler, white eraser, green eraser, red

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pencil, black pencil), and six containers (black box, red box, yellow bag, white bag, blue folder, green folder). There were four types of movements, including “touch”, “push”, “spin”, and “pick up...then put it into”. The movement “touch” required a gentle tap on the object, “push” involved pushing the object forward for a few centimetres, “spin” required making the object revolve once around its own axis and “pick up...then put it into...” were two concatenated movements requiring moving an object to a container. The movement “pick up...then put it in...” was scored as two movements, as participants might combine the correct object with the incorrect container.

Each instruction sentence involved five actions connected using the conjunction word “and”. In an instructional sentence, there was no repetition of the same object and adjacent objects were always in different colors. An example of a typical instruction sentence was, “Touch the yellow ruler, and spin the red pencil, and push the blue ruler, and pick up the black pencil then put it into the blue folder”.

Three lists of instructions were created. Each list contained fourteen instructional sentences (two practice trials and twelve formal trials). A total of 84 different three-digit numbers for the articulatory suppression condition and backward counting condition were randomly generated. Instructions and digits were recorded by a Native British female speaker using normal prosody. The average duration was 9.22s for a sentence and 3 seconds for a three-digit number.

All objects were laid out on a 146cm (length) × 75cm (width) × 71cm (height) desk (see Figure 1). The locations of objects remained same throughout the experiment.

*Design*

In a  $3 \times 2$  mixed design, concurrent task was a within-subject variable including baseline, articulatory suppression and backward counting conditions. Recall was a between-subject variable, including verbal and enactment recall.

### *Procedure*

Upon arrival, each participant was randomly allocated into one of the recall groups. Participants sat at the desk, facing the display of objects. The experimenter sat at a different desk 30 cm away from the participants, controlling the delivery of instructions. All spoken instructions were played through two speakers facing the participant on the experimenter's desk.

All participants completed three concurrent task conditions, counterbalanced in order. The first two trials in each condition were practice. In the baseline conditions, the participant listened to the instruction (lasting about 13 seconds), which was followed by a one second delay and a beep sound, indicating the start of recall. Based on the assigned group, the participant either repeated the instruction back (verbal recall) or performed out the actions (enacted recall). The importance of recalling in sequence was emphasized. The experimenter kept a written record of participants' responses.

The procedure in the articulatory suppression conditions was similar to the baseline conditions except that a participant first heard a three-number digit lasting three seconds prior to each instructional sequence, and began repeating the numbers continuously at a rate of three digits every two seconds. After a further three seconds of repeating the numbers, the instruction began to play. The participant continued repeating the three-digit number aloud while listening to the instructions until the beep sound. The backward counting conditions followed a similar procedure, except that participants counted down from the three-digit number in decrements of two.

## *Results*

### *Correct recall of actions*

Serial recall was scored by averaging the number of correct actions per instruction sequence across the twelve test trials. An action was scored as correct only when the correct combination of movement, color, shape, and serial position were produced. As there were five actions in a sequence, possible scores ranged from 0 to 5. The means and standard deviations of the action are presented in Table 1.

[Table 1 about here]

A  $3 \times 2$  (Concurrent task  $\times$  Recall Type) ANOVA showed a significant main effect of concurrent task,  $F(2, 44)=75.19, p<.001, \eta_p^2=.77, MSE=0.29$ . There was also a significant main effect of recall type, with enactment recall more accurate than verbal recall,  $F(1, 22)=11.81, p=.002, \eta_p^2=.35, MSE=0.32$ . There was no significant interaction between concurrent task and recall,  $F(2, 44)=0.69, p=.506, \eta_p^2=.03, MSE=0.29$ . A series of  $2 \times 2$  ANOVAs were then conducted to test specific dual task effects. We adopted this method because the main aim of this study was to examine the contribution of each working memory component to following instructions. In addition, we wanted to explore whether the involvement of each component would vary with recall type, in order to better understand the enacted recall benefit. A  $2$  (Baseline-Articulatory suppression)  $\times 2$  (Recall Type) ANOVA (intended to examine the role of the phonological loop) revealed a non-significant effect of articulatory suppression,  $F(1,22)=4.00, p=.058, \eta_p^2=.15, MSE=0.22$ , a significant main effect of recall type (enactment recall benefit),  $F(1, 22) =12.62, p=.002, \eta_p^2=.36, MSE=0.77$ , but no interaction between articulatory suppression and recall type,  $F(1, 22)<0.01, p=.964, \eta_p^2<.01, MSE=0.45$ . A  $2$  (Articulatory suppression – Backward counting)  $\times 2$  (Recall Type) ANOVA (designed to examine the contribution of the central executive)

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revealed significant effect of backward counting,  $F(1,22)=99.63$ ,  $p < .001$ ,  $\eta_p^2 = .82$ ,  $MSE=0.27$ , a significant enactment recall benefit,  $F(1,22)=8.57$ ,  $p = .008$ ,  $\eta_p^2 = .28$ ,  $MSE=0.77$ , but no significant interaction between backward counting and recall type,  $F(1, 22)=1.07$ ,  $p=.312$ ,  $\eta_p^2 = .05$ ,  $MSE=0.53$ .

#### *Movement and feature binding scores*

As a secondary form of analysis, we examined memory for movements, and for binding additional features (i.e., colors and objects) to these movements. This scoring approach adopted two levels of analysis. As the task is based on following instructions for sets of movements, the first scoring level adopted was that of movement. A movement was scored as correct if it was accurately recalled in the appropriate serial position in the sequence, irrespective of associated object and color. This produced a total score for the number of movements correctly produced in each condition. The second level of scoring (feature binding) measures the linkage of component features (i.e. color, object) to each movement. In order to index binding between features and movements, a feature binding score was calculated based on the number of features that were correctly recalled in conjunction with the appropriate movement. Note that as each movement was potentially associated with two features (i.e., color and object), the Feature Binding score could be up to twice the level of the Movement score. Finally, in order to examine accuracy in binding features to movements while controlling for success in recalling the movements themselves, a proportional feature binding score was calculated, by dividing the feature binding score by the maximum number of features each participant could have recalled, given their movement recall<sup>1</sup>. As this proportional score reflects the ability to bind additional features to movements independently of the accuracy of recalling the movements themselves, only the proportional measure was entered into statistical analysis.

As each condition comprised 60 movements and 120 associated features (i.e., colors and objects) in total, the movement scores ranged from 0 to 60 and the feature binding scores ranged from 0 to 120. The proportional feature binding scores had a range of 0 to 1. The means and standard deviations for each of these outcomes across the experimental conditions are displayed in Table 2. The movement and proportional feature binding outcomes were entered into 3 x 2 and 2 x 2 analyses of variance, following the approach applied in the examination of action recall. In all experiments, only outcomes that differ from the analysis of overall action recall will be reported, for the sake of concision. In fact, for Experiment 1, analysis of movement and feature binding produced generally equivalent outcomes to action (movement-object pair) recall, with non-significant effects of articulatory suppression, large disruptive effects of backward counting, an enacted recall advantage, and no concurrent task by recall type interactions.

[Table 2 about here]

### *Discussion*

The ability to follow instructions was not significantly disrupted by simple articulatory suppression, but was greatly impaired by backward counting. These findings provide little evidence for a phonological loop contribution to the encoding and/or maintenance of spoken instructions. This may be because the amount of verbal information to be retained (sequences contained between 24 and 29 words) exceeded the capacity of the loop leading to strategic abandonment use of rehearsal, a phenomenon noted under other conditions of heavy verbal memory loads (Salamé & Baddeley, 1986). Similarly, the binding of visual features with movements was similarly unaffected by suppression. However, it should be noted that the effect of suppression was not far from the conventionally accepted level of significance that is

typically applied in classic inferential statistics ( $p = .058$ ) and had a large effect size ( $\eta_p^2 = .15$ ), and thus we would not strongly reject a role for phonological short-term memory in this task.

The adverse effect of backward counting on the recall of actions suggests a substantial contribution of the central executive to the encoding of instructions in line with findings from tasks involving the written presentation of instructions (Yang et al., 2014) and of sentences (Baddeley et al., 2009). It also impaired both the recall of movements and the binding of features, suggesting that the central executive may be involved in encoding sequential movements and binding these with target objects as well as in controlling the flow of information through working memory, utilizing environmental support, and selecting strategies in order to support performance (Baddeley, 1986), and maintaining access to representations (Allen, Baddeley, & Hitch, 2014). The finding that an executive load disrupts linkage of movements to objects might suggest binding processes in this context to be attention-demanding, although as the influence of backward counting extended across all outcomes measures, this may be broadly equivalent for features and their bindings (Baddeley et al., 2011).

As with written instructions (Yang et al., 2014), there was a significant benefit to enacting over verbally repeating the instruction sequence, and this was unaffected by concurrent tasks. Neither the phonological loop nor the central executive components of WM are therefore potential sources of this effect. Enactment also increased the accuracy of recall of movements and the binding of features.

### Experiment 2

The visuospatial sketchpad has been proposed to encode and retain visual, spatial and motoric information in WM (Logie, 1995). It might therefore be expected to be

involved in the construction of representation for the following of spoken instructions. In particular, visuospatial working memory may be involved in binding of movement with colored objects located in different locations. This hypothesis was tested in Experiment 2, in which a spatial tapping task was applied to disrupt the contribution of the visuospatial sketchpad component of WM. This task involves tapping in a specific pattern of spatial locations continuously at a paced rate, and has been suggested to load on the spatial component of the visuospatial sketchpad (Farmer, Berman, & Fletcher, 1986; Klauer & Zhao, 2004; Salway & Logie, 1995; Smyth et al., 1988). In addition to a baseline condition of no concurrent task, an articulatory suppression condition was also included for the purposes of comparison.

### *Method*

#### *Participants*

Twenty-four native English speakers aged from 18 to 27 at the University of York were recruited. None of the participants took part in Experiment 1.

#### *Materials*

The instructional materials were similar to those in Experiment 1 except that all four types of actions were included in each sentence without repetition of movements in this experiment. Three lists of instructions were constructed. Each list included fourteen instructional sentences, with two practice trials and twelve formal trials. The numerical keypad of a standard Dell keyboard was adapted into a four key device, with four keys at the corners (number 7, 9, 1, 3) and all other keys removed. The keypad was hidden from the view of participants and placed near the dominant hand side of the participant.



As this experiment focused on investigating the contribution of spatial coding in the process of following instructions, the visual display of objects were more dispersed to increase the spatial WM demands (see Figure 1). In addition, in order to emphasize WM storage and the temporary nature of object-spatial relationships, the display changed between trials, to ensure each trial resembled a new learning environment; nevertheless, within a trial (i.e. during the encoding and recall stage) the visual display remained the same.

### *Design*

In a 3×2 mixed design, concurrent task was set as the within-subject variable including baseline, articulatory suppression and tapping condition; and recall type was a between-subject variable, including verbal and enactment recall.

### *Procedure*

The procedure was similar to that of Experiment 1. Each participant performed three conditions, namely, baseline, articulatory suppression, and tapping. The baseline condition was identical to that used in Experiment 1. In the articulatory suppression condition, participants were first presented with the auditory sequence “1-2-3-4” (three seconds in duration), and repeated it aloud at the same rate continuously. After a further three seconds of repetition, participants heard the spoken instructions and continued to repeat “1-2-3-4” throughout instruction presentation and the one-second delay until the beep sound, at which point they began to recall. In the tapping condition, upon hearing the command “start”, participants began to tap the four keys 1-7-9-3 clockwise on the keypad at an approximate pace of three seconds per circle. After a further three seconds, the participant heard the instructional sentences while continuing tapping until the beep sound. Participants were told to only use their forefingers to tap. After the beep sound, the participant either repeated the instruction

back or performed the actions according to the assigned group. At the end of each trial, the experimenter randomly changed the locations of three objects on the table, with participants asked to close their eyes during this change.

### *Results*

All scoring methods were same as in Experiment 1. The means and standard deviations of these scores are presented in Table 1 and 2.

#### *Correct recall of actions*

A  $3 \times 2$  (Concurrent task  $\times$  Recall) ANOVA revealed a significant main effect of concurrent task,  $F(2, 44)=3.69$ ,  $p=.033$ ,  $\eta_p^2=.14$ ,  $MSE=0.31$ . There was also a significant main effect of recall type, with superior performance of recall by enactment than by oral repetition,  $F(1, 22)=4.70$ ,  $p=.041$ ,  $\eta_p^2=.18$ ,  $MSE=0.64$ . The interaction between concurrent task and recall type was not significant,  $F(1, 22)=0.62$ ,  $p=.544$ ,  $\eta_p^2=.03$ ,  $MSE=0.31$ . As in Experiment 1, further  $2 \times 2$  analyses were then performed to examine contributions of the phonological loop and spatial working memory respectively. A  $2$  (Baseline-Articulatory suppression)  $\times 2$  (Recall Type) ANOVA revealed a significant effect of articulatory suppression,  $F(1, 22)=7.21$ ,  $p=.013$ ,  $\eta_p^2=.25$ ,  $MSE=0.27$ , a non-significant enactment recall benefit,  $F(1, 22)=4.28$ ,  $p=.051$ ,  $\eta_p^2=.16$ ,  $MSE=0.53$  (though this outcome was close to the conventionally accepted level of significance), and no significant interaction between articulatory suppression and recall type,  $F(1, 22)=0.17$ ,  $p=.682$ ,  $\eta_p^2<.01$ ,  $MSE=0.27$ . A  $2$  (Baseline – Tapping)  $\times 2$  (Recall Type) ANOVA revealed a non-significant effect of tapping,  $F(1, 22)=3.54$ ,  $p=.073$ ,  $\eta_p^2=.14$ ,  $MSE=0.39$ , a significant enactment recall benefit,  $F(1, 22)=4.94$ ,  $p=.037$ ,  $\eta_p^2=.18$ ,  $MSE=0.75$ , and no significant interaction between backward counting and recall type,  $F(1, 22)=0.39$ ,  $p=.537$ ,  $\eta_p^2=.02$ ,  $MSE=0.39$ .

*Movement and binding scores*

Outcomes are displayed in Table 2. As in Experiment 1, 3 x 2 and 2 x 2 analyses of variance revealed broadly equivalent patterns of outcomes to those observed in the correct recall of actions (movement-object pairs), with a few notable differences.

Firstly, articulatory suppression had a significant disruptive effect on movement recall (relative to baseline),  $F(1, 22)=6.28, p=.020, \eta_p^2=.22, MSE=33.15$ , but did not impact on the feature binding measure,  $F(1,22)=0.35, p=.561, \eta_p^2=.02, MSE<0.01$ .

Secondly, while the effect of spatial tapping (relative to baseline) on movement recall remained non-significant,  $F(1, 22)=3.46, p=.076, \eta_p^2=.14, MSE=42.45$ , this effect was significant for the proportional feature binding score,  $F(1,22)=5.84, p=.024, \eta_p^2=.21, MSE<0.01$ . Thus, the two concurrent tasks implemented in this experiment had distinct impacts on movement and binding recall, with articulatory suppression primarily impacting on the former outcome, and spatial tapping on the latter.

*Discussion*

Experiment 2 replicated the enactment benefit of actions reported in Experiment 1. Articulatory suppression significantly disrupted recall of actions but as in Experiment 1 did not interact with recall type, suggesting a consistent contribution of the phonological loop regardless of whether recall involves verbal repetition or physical enactment. Similarly, articulatory suppression did not significantly reduce the binding of object features to correct movement, possibly again suggesting the minimal contribution from the phonological loop in binding movements with objects, but did affect memory for the movements themselves. This could suggest that participants employ a verbal code to help retain movement information, though this effect did not emerge in Experiment 1 and so may not be reliable.

Spatial tapping did not significantly impair the recall of actions and movements, although it did reduce the proportion of features that were accurately combined. We used a standard version of spatial tapping in this experiment, which has previously been demonstrated to have clear and consistent effects on spatial reasoning (Farmer et al., 1986), spatial imagery (Salway & Logie, 1995), and spatial span (Della Sala, Gray, Baddeley, Allemano, & Wilson, 1999; Smyth & Pendleton, 1989). Therefore, this task does place meaningful demands on spatial WM resources. The observation that interfering with spatial representation via the tapping task only substantially and reliably impaired feature binding suggests one role of spatial WM in following instructions to be in linking movements with potential objects located in the environment.

### Experiment 3

Recent explorations of the ability to following instructions have generally involved objects being in view during presentation of instructions. Thus, participants may utilize these visual cues to help build a richer and more robust representation, suggesting a role for visual storage working memory. In order to examine this, access to the visual display during encoding was blocked entirely in this final experiment by requiring participants to close their eyes during the instruction presentation phase. If the visual encoding of objects is indeed crucial, then removing the visual display as a source of information should subsequently impair recall. Moreover, this may force participants to rely on verbal storage and rehearsal, leading to a verbal-based representation for both types of recall. If this is the case, enacted recall accuracy should decline to a relatively greater extent than verbal recall.

## *Method*

### *Participants*

A further twenty-four native English speakers aged 18-47 years attended the experiment. None of the participants took part in Experiment 1 or 2.

### *Materials*

Materials were the same as those in Experiment 2, except an additional set of instruction sequences were added given there were four conditions in this experiment.

### *Design*

In a  $2 \times 2$  within-subject design, participants either opened or closed their eyes during encoding, followed by either verbal or action recall. Conditions were implemented in a counterbalanced order. The measurements were the same as those in the previous two experiments.

### *Procedure*

All participants completed four conditions. The eye-open conditions were the same as the baseline conditions in Experiment 2. In the eye-closure conditions, participants were instructed to close their eyes throughout the presentation of instructions until the beep sound, upon which they opened their eyes and began recall. As in Experiment 2, the locations of objects were randomly moved between trials. Strategies were probed at the end of each condition, with a single question, that is, “if you are using any strategy, please state”.

## *Results*

All scoring methods were identical to the previous two experiments. The means and standard deviations of these scores are presented in Table 1 and 2.

### *Correct recall of actions*

A  $2 \times 2$  (Eye-closure  $\times$  Recall) ANOVA revealed a significant main effect of eye-closure,  $F(1, 23)=191.58$ ,  $p < .001$ ,  $\eta_p^2 = .89$ ,  $MSE=0.24$ , with closure having a substantial detrimental impact on performance. There was also a significant main effect of recall type, with action recall superior to verbal recall,  $F(1, 23)=109.29$ ,  $p < .001$ ,  $\eta_p^2 = .83$ ,  $MSE=0.14$ . The interaction between eye-closure and recall was not significant,  $F(1, 23)=1.38$ ,  $p = .252$ ,  $\eta_p^2 = .06$ ,  $MSE=0.16$ .

#### *Movement and binding scores*

Mean performance levels for each response measure are presented in Table 2.

Applying a  $2 \times 2$  ANOVA to each measure produced identical outcomes to those observed in overall action recall, that is, a significant disruptive effect of eye closure, an enacted recall advantage, and no interaction between these factors.

#### *Discussion*

Eye closure during encoding of instructions substantially impaired recall of actions, indicating that visual information is used to encode spoken instructions. Similarly, eye closure reduced the accuracy of recalling movement and of binding features, suggesting that these elements normally rely on visual support. This is consistent with a shift in strategy as a result of eye closure that can be observed in the subjective reports (see Appendix): visual tracking was preferred when coding the locations of objects was possible in the eye-open conditions, but when it became impossible in the eye-closure conditions, participants often switched to strategies such as verbal rehearsal and imagined enactment. These outcomes suggest that visual tracking may be a critical strategy in linking movements with targeted objects in particular, and in encoding and maintaining instructions in general.

The enactment benefit in following instructions found in previous studies (e.g., Gathercole et al., 2008; Yang et al., 2014) and in Experiments 1 and 2 was replicated

once more. A new finding was that this effect remained with eyes closed at encoding, contrary to the hypothesis that preventing visual coding would lead to dependence on verbal representations of instructions irrespective of recall condition and thereby eliminate the enactment effect. The strategy reports are also inconsistent with this hypothesis: 46% of participants imagined themselves performing the actions and 38% of participants rehearsed the spoken commands in eye-closure conditions, suggesting the representations in eye-closure conditions were mixed rather than purely verbal-based. This mixed representation may be more effective in guiding enactment than oral repetition, which would explain the emergence of the enactment benefit even in eye-closure conditions.

### General Discussion

Findings from three experiments reinforce previous evidence of a close relationship between WM and the capacity to following instructions (Brenner, 1940; Engle et al., 1991; Gathercole et al., 2008; Kim et al., 2008). A range of manipulations (designed to disrupt different components of working memory) that were applied during auditory-verbal presentation of instructions disrupted subsequent verbal and enacted recall to an equivalent extent, in line with findings observed by Yang et al. (2014) using visual presentation of instructions. Overall, broadly similar outcomes were observed when examining recall of movement-object chunks, and when distinguishing recall into its constituent components of movements, visual features and their binding. The latter form of analysis was applied in order to explore the following instructions paradigm in the context of feature binding and the proposed episodic buffer component of working memory (Baddeley, 2000; Baddeley et al., 2011). For the most part, high levels of proportional feature binding accuracy were observed in baseline conditions across the three experiments. This reveals that when

the participant accessed each action ‘chunk’ (see also Gilchrist, Cowan, & Naveh-Benjamin, 2009; Naveh-Benjamin, Cowan, Kilb, & Chen, 2007) by recalling the correct movement, they were highly likely to then complete this chunk by producing the appropriate object (in terms of both color and form), potentially indicating that partial loss of binding information in this paradigm was relatively rare. Movement-object chunks may therefore be encoded, retained (possibly within the episodic buffer), and accessed at retrieval in an all-or-none manner, at least when working memory resources are not directed elsewhere.

In Experiment 1 and 2, reduced performance of recall of actions by articulatory suppression was observed, indicating some involvement of the phonological loop. As auditory-verbal presentation is assumed to gain direct access to the phonological store (Baddeley, 2007), the phonological loop might be the initial buffer that stores verbal information, before information is translated into other forms for storage or before a multimodal representation is developed. Articulatory suppression however showed little impact on the measure of feature binding, indicating that the contribution of temporary phonological storage to the binding of movement and object is relatively minimal.

In contrast, our findings indicated an active role for the central executive in overall action recall, for movement, and in binding movements and objects. The central executive clearly plays a substantial role in memorizing instructions, consistent also with other studies examining verbal recall of extended and structured verbal sequences (Baddeley et al., 2009). Possible contributions may include the encoding and retention of auditory-verbal sequences and the allocation of attention to relevant objects to enable visuospatial encoding. Outcomes of the feature binding analysis from Experiment 1 also suggest that the central executive may be associated



to some extent with the creation and/or maintenance of binding within movement-object-location chunks held in memory for the purposes of either performance or verbal recall. However, we would note that concurrent backward counting impacted on all outcome measures in Experiment 1 (recall of action pairs, along with movements and binding of movement to object features). This would indicate that the central executive likely plays a general role in supporting all elements of performance, rather than specifically supporting feature binding (Allen et al., 2006; Allen, Hitch, Mate, & Baddeley, 2012; Baddeley et al., 2011).

Interfering with spatial coding by concurrent spatial tapping during encoding led to a relatively small and non-significant recall decrement, whereas when visuospatial cues were completely blocked via eye-closure, the performance of both verbal and enacted recall dropped significantly. These results thus suggest that visual and spatial information are encoded even when instructions are delivered in a verbal-based form. The observation of tapping and eye closure effects on overall action recall and on feature binding is in line with subjective reports from Experiment 3 showing that visual tracking was the most frequently used strategy in the eye open condition. These findings suggest that memory for instructions, including binding movements with objects, at least partly relies on visuospatial WM, perhaps through orienting attention to objects while building a sequential representation of spatially coded movements. This is consistent with the finding of a previous study that visuospatial WM capacity predicted the learning of new motor sequences (Bo & Seidler, 2009), and is also in line with the suggestion that successful verbal-visuospatial binding within the episodic buffer draws on spatial working memory resources (Allen, Havelka, Falcon, Evans, & Darling, 2015).

Across all three experiments, a reliable enactment benefit emerged, consistent with research in children (Gathercole et al., 2008) and using written instruction with young adults (Koriat, Ben-Zur, & Nussbaum, 1990; Yang et al., 2014). The enactment advantage was not influenced by any of the four encoding manipulations employed in this series of experiments, a pattern of findings corresponding closely to that obtained with printed instructions (Yang et al., 2014). Additionally, a novel outcome in this study is that the enactment advantage also extended to the binding of movements and objects, and that this was again not mediated by disruption of WM resources. It is therefore concluded that the enactment advantage does not rely on the central executive, phonological loop, or visuospatial sketchpad aspects of working memory as described in the Baddeley and Hitch (1974) multicomponent model. What, then, is the source of the enactment advantage in following instructions? One possibility is that anticipated enactment leads to the creation of a motoric-based representation during encoding that better supports later recall. Such an account has previously been proposed to capture encoding-based enactment (or Subject-Performed Task) effects in measures of long-term memory (e.g., Engelkamp & Zimmer, 1989; Freeman & Ellis, 2003; Nyberg et al., 2001; Saltz & Donnenwerth-Nolan, 1981), and may also apply to the recent observation that this manipulation boosts verbal more than enacted recall in a working memory context (Allen & Waterman, 2015). Thus, anticipation and mental simulation of intended physical enactment may have a motoric component equivalent to that produced by actual enactment, and with similar benefits to working memory performance. This may combine with other forms of representation in the episodic buffer, and serve to strengthen links between movement and object in space, thus forming a spatial-motoric representation of actions in sequence.

One possibility is that the enactment benefit might also at least partly emerge during maintenance and retrieval, given that the concurrent tasks in the present study (and in Yang et al., 2014) were applied during encoding. For instance, expecting to perform at recall may help maintain movement-object binding more effectively. Similarly, during enacted recall, each movement-object chunk is implemented as a movement in space that is compatible with the original representation. In contrast, for verbal recall, each pairing may be disassembled into a sequential verbal output of ‘movement-color-object’, a process that may be error-prone. Indeed, while visual tracking and imagined enactment were the most frequently reported encoding-based strategies for both verbal and enactment recall types, the forms of representation emphasized by these strategies may be more suitable for enacted recall. However, a purely output-based enactment advantage is unlikely; this effect appears to be substantially reduced when participants physically enact during encoding (Allen & Waterman, 2015), and recall success has been found to depend heavily on expected rather than actual mode of report (Koriat et al., 1990). Nevertheless, exploring interactions between encoding and retrieval, and the forms of representation involved, would be a useful focus for future research.

Finally, a major motivation in understanding the cognitive underpinnings of this paradigm lies in subsequent development of methods and techniques to assess and support instruction following across different populations, age groups and environments. However, it should be noted that working memory capacity undergoes substantial development from early childhood to young adulthood (e.g., Gathercole, Pickering, Ambridge, & Wearing, 2004), before declining with healthy aging (e.g., Park et al., 2002). Therefore, in order to best support development of practical applications, it would be of value to systematically explore how the ability to follow

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instructions changes across the lifespan, and how different components of working memory might contribute to this.

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## Footnote

1. For example, if a participant correctly recalled all five actions in a given trial except for a color error on the final action, then Movement score = 5, maximum possible number of features recall = 10, Feature Binding score = 9 (4 colors + 5 objects), and proportional Feature Binding score = .90 (Feature Binding score/Maximum possible number of features, i.e. 9/10).

## Appendix

The subjective reports of strategies used for following instructions in Experiment 3 were summarized and presented in Table A1. The numbers and percentages of responders indicating using that strategy were calculated for each strategy using count and percentage scores.

Table A1

The Subjective Reports of Strategies Used for Following Instructions in Experiment 3

	Verbal recall		Enactment Recall		Total	
	Count	Percent	Count	Percent	Count	Percent
	(N=12)		(N=12)		(N =24)	
Eye open						
Visual tracking	7	58%	8	67%	15	63%
Imagined enactment	3	25%	3	25%	6	25%
Rehearsal	0	0%	0	0%	0	0%
Grouping actions	0	0%	0	0%	0	0%
Eye closure						
Visual tracking	0	0%	0	0%	0	0%
Imagined enactment	5	42%	6	50%	11	46%
Rehearsal	5	42%	4	33%	9	38%
Grouping actions	1	8%	0	0%	1	4%

## Tables

Table 1. Means (standard deviations) of actions in three experiments

	Verbal recall	Enactment recall	Mean
Experiment 1			
Baseline	2.95 (0.79)	3.86 (0.62)	3.41 (0.84)
Articulatory suppression	2.69 (0.78)	3.58 (0.61)	3.13 (0.82)
Backward counting	1.35 (0.76)	1.94 (0.71)	1.65 (0.78)
Mean	2.33 (0.61)	3.12 (0.53)	2.73 (0.69)
Experiment 2			
Baseline	3.44 (0.79)	4.11 (0.87)	3.78 (0.88)
Articulatory suppression	3.10 (0.81)	3.65 (0.80)	3.37 (0.83)
Tapping	2.98 (1.18)	3.89 (1.01)	3.44 (1.17)
Mean	3.18 (0.80)	3.88 (0.80)	3.53 (0.86)
Experiment 3			
Eye open	2.98 (0.77)	3.77 (0.66)	3.37 (0.67)
Eye closure	1.69 (0.61)	2.29 (0.70)	1.99 (0.61)
Mean	2.33 (0.60)	3.03 (0.62)	2.68 (0.59)

Table 2. Means (standard deviations) of Movement, Feature Binding, and Proportional Feature Binding scores in three experiments

		Movement	Feature Binding	Proportional Feature Binding
Experiment 1				
Verbal recall	Baseline	39.00 (8.70)	72.17 (17.94)	0.92 (0.05)
	Articulatory suppression	37.83 (8.54)	67.17 (18.62)	0.88 (0.08)
	Backward counting	25.00 (9.29)	35.17 (18.78)	0.69 (0.17)
Enactment recall	Baseline	48.17 (6.34)	93.08 (13.75)	0.97 (0.04)
	Articulatory suppression	46.08 (6.24)	87.33 (13.88)	0.95 (0.04)
	Backward counting	30.17 (8.52)	48.00 (17.35)	0.78 (0.13)
Experiment 2				
Verbal recall	Baseline	44.67 (7.81)	83.58 (18.67)	0.93 (0.06)
	Articulatory suppression	39.67 (9.24)	75.50 (19.17)	0.95 (0.03)
	Tapping	40.08 (13.53)	73.33 (28.34)	0.90 (0.08)
Enactment recall	Baseline	50.33 (9.96)	99.17 (20.63)	0.98 (0.02)
	Articulatory suppression	47.00 (9.30)	89.92 (19.89)	0.95 (0.05)
	Tapping	47.92 (11.76)	91.17 (25.98)	0.94 (0.07)
Experiment 3				
Verbal recall	Eye open	40.71 (9.02)	73.63 (19.09)	0.90 (0.07)
	Eye closure	29.79 (7.64)	43.67 (13.91)	0.73 (0.12)
Enactment recall	Eye open	47.67 (7.35)	91.29 (15.11)	0.96 (0.03)
	Eye closure	37.79 (7.93)	59.25 (17.65)	0.77 (0.11)

*Note.* Movement score represents the number of correct movement in a condition. Feature Binding score represents the number of additional features attached to the correct movement in a condition. Proportional Feature Binding scores indicates the proportion of correct features attached to the correct movement.

## Figures

Figure 1. Visual display of the instructional task.

