Comparing motor imagery and verbal rehearsal strategies in children's ability to follow spoken instructions

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The ability to follow spoken instructions is important for effective learning (Gathercole & Alloway, 2008). In the classroom, children constantly receive spoken instructions from teachers, which they need to retain and implement over short periods of time. Recent work indicates that the ability to remember instructions relies on different components of working memory as described within Baddeley and Hitch's multicomponent framework (Baddeley, 1986, 2000; Baddeley, Hitch, & Allen, 2020), with the phonological loop retaining verbal information, and the visuospatial sketchpad storing visual and spatial information. More recently, it has been suggested that motor information might also be maintained in order to support subsequent performance, either as an information stream within the visuospatial sketchpad or as a separate spatial-motor system that maintains motor sequences (Jaroslawska, Gathercole, & Holmes, 2018; Li, Allen, Hitch, & Baddeley, under review). Finally, the central executive coordinates these storage systems and facilitates binding of information (Jaroslawska et al., 2018; Yang, Allen, & Gathercole, 2016; Yang, Gathercole, & Allen, 2014).

Retaining spoken instructions relies on working memory: a system with limited capacity in which information is rapidly lost unless it is refreshed or restored through processes of active maintenance. A natural and convenient way of maintaining verbal information in working memory is verbal rehearsal: repeating the memory content overtly (i.e., out loud) or covertly (i.e., silent or sub-vocal rehearsal). The ability to engage with verbal rehearsal strategies is evident by the age of 7 years, and this ability improves over middle childhood (Gathercole, 1998; Tam, Jarrold, Baddeley, & Sabatos-DeVito, 2010). Research investigating the ability to follow spoken instructions in a working memory paradigm suggests that adults rely on multiple components of working memory when performing the task (Yang et al., 2016), whereas children's performance is primarily linked to their verbal working memory ability (Jaroslawska, Gathercole, Logie, & Holmes, 2015).

Besides verbal rehearsal, given that instructions contain action information, motor imagery/rehearsal at encoding may also serve to boost recall. Motor imagery refers to the process of internally reproducing action representations in working memory without overt action output (Decety & Grèzes, 1999). The motor imagery process often involves different modalities (e.g., kinesthetic, visual, spatial) (Smyth & Waller, 1998), and through this process people form a motor image as if they were actually performing the actions (Annett, 1995; Munzert, Lorey, & Zentgraf, 2009). Within the motor imagery literature, imagery produces an internal forward model that predicts the process of action execution (Wolpert, 1997), and simulates actual execution by activating similar brain networks (i.e., frontoparietal areas and subcortical structures) in advance (Hétu et al., 2013). Motor imagery is widely used in different disciplines (e.g., sports, music, rehabilitation) to improve performance over the long term (Schuster et al., 2011). However, to our knowledge, no published study has examined the immediate effect of motor imagery on following instructions with child participants. An initial study with adult participants has found that imagining acting out the instructions at encoding (compared with not imagining) boosted subsequent recall, but these preliminary findings require replication, and have not been studied in children (Waterman & Allen, 2019).

While there is limited evidence for the benefit of motor imagery in following instructions in working memory, several other lines of research support the possibility. First, forms of enactment similar to motor imagery show clear facilitative effects on following spoken instructions. For instance, observing others' performing the actions during encoding improved following instruction performance in both young adults (Allen, Hill, Eddy, & Waterman, 2019; Lui et al., 2017; Yang, Allen, Yu, & Chan, 2015; Yang, Jia, Zheng, Allen, & Ye, 2019) and children (Waterman et al., 2017). Similarly, self-performance of the actions during encoding also led to superior following instruction performance in adults (Allen & Waterman, 2015; Lui et al., 2017) and children (Jaroslawska, Gathercole, Allen, & Holmes, 2016; Waterman et al., 2017; Wojcik, Allen, Brown, & Souchay, 2011), as long as the instructions were not too demanding for children (Waterman et al., 2017).

Second, there are consistent findings of an enacted-recall advantage in following spoken instructions in young adults, with superior memory of spoken instructions by enacted recall compared with oral repetition at recall. Researchers have suggested this arises from the representation generated by action planning/motor imagery at encoding when anticipating enactment at recall, compared with verbal-based representation formed by verbal rehearsal when anticipating oral repetition at recall (Allen & Waterman, 2015; Koriat, Ben-Zur, & Nussbaum, 1990; Lui et al., 2017; Yang et al., 2016; Yang et al., 2015; Yang et al., 2019). In line with this interpretation, the concurrent performance of certain types of motor movement tasks during encoding has been shown to reduce, and even remove, the enacted recall advantage (Jaroslawska et al., 2018; Li et al., under review), indicating a specific component to this effect that is separable from those involved in encoding verbal sequences more generally.

This advantage for enacted over verbal recall in following spoken instructions has also been observed in children aged 5 to 11 years (Gathercole, Durling, Evans, Jeffcock, & Stone, 2008; Jaroslawska et al., 2016; Waterman et al., 2017; Yang, Allen, Holmes, & Chan, 2017), implying children can also utilize action planning/motor imagery to encode and retain the to-be-performed actions. This is consistent with evidence from developmental studies of motor imagery skill within human movement science which shows that children can utilize motor imagery from as young as 5 years of age, although several studies suggest that they may not be able to engage fully with motor imagery until the age of 10 (Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009; Spruijt, van der Kamp, & Steenbergen, 2015). Finally, a study by Miller, McCulloch, and Jarrold (2015) found that 5- to 9-year-olds' performance on a short-term memory task for images was improved when children were introduced to an interactive-imagery strategy (i.e., in the interstimulus gaps, all the previous images were shown in the corner of the computer screen), or a verbal rehearsal strategy (i.e., sound files with visual cues to demonstrate cumulative rehearsal), before the short-term memory task. However, children were not explicitly instructed to use either of these strategies during the short-term memory task so some caution is needed when interpreting these findings. Overall, these studies lend support to the idea that motor imagery may have a facilitative effect on instruction following in children.

In addition to the limited research on motor imagery in following instructions, no study has directly compared the effectiveness of explicitly instructing children to use different encoding strategies - motor imagery and verbal rehearsal - for memorizing instructions. The finding of the enacted-recall advantage implies superior representation based on action planning/motor imagery compared with verbal rehearsal (Jaroslawska et al., 2018; Yang et al., 2016), motor imagery may be a better encoding strategy than verbal rehearsal, and could lead to better memory for instructions.

Taken together, both verbal rehearsal and motor imagery may improve children's ability to follow spoken instructions. This study aims to test and compare the effects of the two encoding strategies in school-age children. We used an instruction span task adapted from previous work (Gathercole et al., 2008; Yang et al., 2017), which required children to remember sequences of action commands involving manipulation of stationery objects. Additional time for the specific encoding strategy (i.e., verbal rehearsal or motor imagery) was added after presentation of each action-object pair (Allen & Waterman, 2015; Waterman et al., 2017). Moreover, we examined whether the effect of encoding strategy would vary with recall modality. Self-enactment at encoding has been shown to benefit verbal recall more than enacted recall, in adults (Allen & Waterman, 2015; Lui et al., 2017) and children (Jaroslawska et al., 2016; Waterman et al., 2017, Exp 2b). A more mixed pattern is apparent for observing enacted demonstration by others; although Lui et al. (2017) found larger benefits for verbal recall in an adult sample, this interactive effect was not observed in other studies featuring adults (Yang et al., 2015) or children (Waterman et al., 2017, Exp 2a). Due to these somewhat inconsistent outcomes, and the absence of previous research directly comparing imagery and rehearsal-based encoding on verbal and enacted recall, no priori hypothesis was made on this point.

The second aim of the present study is to examine the developing course of the ability to follow spoken instructions from age 7 to 12, and to explore whether the effect of encoding strategies varies with age. No studies to date have investigated the effect of using different encoding strategies on children's performance on a following instruction task in working memory. The motor learning literature suggests that children younger than 10 years of age may not engage with mental imagery manipulations as effectively, but this is within a different paradigm and these studies did not relate imagery to memory ability. As such, we made no specific predictions on whether different encoding strategies would show different developmental trajectories. However, given the continuous improvement of working memory in this age group (Gathercole, 1998) and the close association between working memory and instruction-following in children (Jaroslawska et al., 2015), we did expect an overall age-related increment in the ability to recall spoken instructions.

Method

Participants

A total of 146 children between 7 and 12 years old were recruited from a primary school in China. There were 41 children between age 7 and 8 (21 boys, 20 girls, mean age was 8 years 1 month), 65 children between age 9 and 10 (31 boys, and 34 girls, mean age was 9 years 11 months), 40 children between age 11 and 12 (21 boys and 19 girls, mean age was 11 years 6 months). All the children were native Chinese speakers.

Design

The study adopted a 2 (encoding strategy: imagery vs. rehearsal) × 2 (recall modality: verbal vs. enacted) × 3 (age group: 7-8, 9-10,11-12) mixed design. The encoding strategy and recall modality were within-subject variables, and age group was a between-subject variable. The order of the four test conditions was counterbalanced across different age groups using the Latin square design. The dependent variables were action-object pairs, and the separate feature scores (action and object). An action-object pair (e.g., tap the red pencil) was considered correct when the elements (i.e., action, object, and serial position) were all correct. The two features of the action-object pairs (action, and object) were also scored separately. The action was scored as correct when the correct action was carried out in the correct serial position, independent of the accuracy of the associated object. Similarly, the object score was scored as correct when the correct object was recalled in the correct serial position, independent of the accuracy of the associated action. The scores of action-object pairs and of the features (i.e., action and object) were transformed into proportion correct (i.e., range from 0 to 1).

The instruction span task

The instruction span task was adapted from the spoken-instruction subtest used by Yang et al. (2015) where the spoken instructions were sequences of action-object manipulations. There were six objects (a white eraser, a green eraser, a blue ruler, a yellow ruler, a red pencil and a black pencil), and six types of movements (pull, push, tap, lift, flip, spin).

The task included four parallel instruction lists, with each list containing three blocks of four trials with equal numbers of action-object pairs. The first block contained two action-object pairs (e.g., tap the white eraser, pull the yellow ruler), the second block contained three action-object pairs (e.g., flip the blue ruler, spin the white eraser, pull the black pencil), and the fourth block contained four action-object pairs (e.g., push the green eraser, spin the blue ruler, flip the red pencil, lift the white eraser). In each instruction trial, the actions and objects were all different. All the action-object pairs were read and recorded by a native Chinese female speaker at a moderate speed, and each instruction was edited into an auditory file.

Children were tested individually by an experimenter in a quiet classroom of a primary school. In each condition, the child sat at a desk facing the row of six objects. The location of the objects remained the same throughout the test. The experimenter first told the child that she/he was going to play a memory game. The experimenter then introduced the names of the objects and the actions, demonstrated the actions, and the children were given practice until they could name all the objects and perform all the actions correctly.

After this, the experimenter explained to the children that they would hear a series of instructions which they would need to memorize and then recall. The children were told that they would be asked to use a specific strategy to help them remember the instructions, and that sometimes they would have to repeat the instructions verbally, and sometimes they would have to act them out. The paradigm was similar to that used in the Waterman et al. study (2017). As shown in Figure 1, each trial began with the experimenter saying ‘prepare’, and after a 500ms silence, children heard the first action-object pair, followed by a silent 2.5 s time window for motor imagery or verbal rehearsal (depending on the condition), and then they heard the second action-object pair, followed by another silent time window, and so on. The end of the instruction sequence was indicated by a beep sound, when children had to recall the instructions either by oral repetition (the verbal-recall condition) or by performing the actions (the enacted-recall condition).

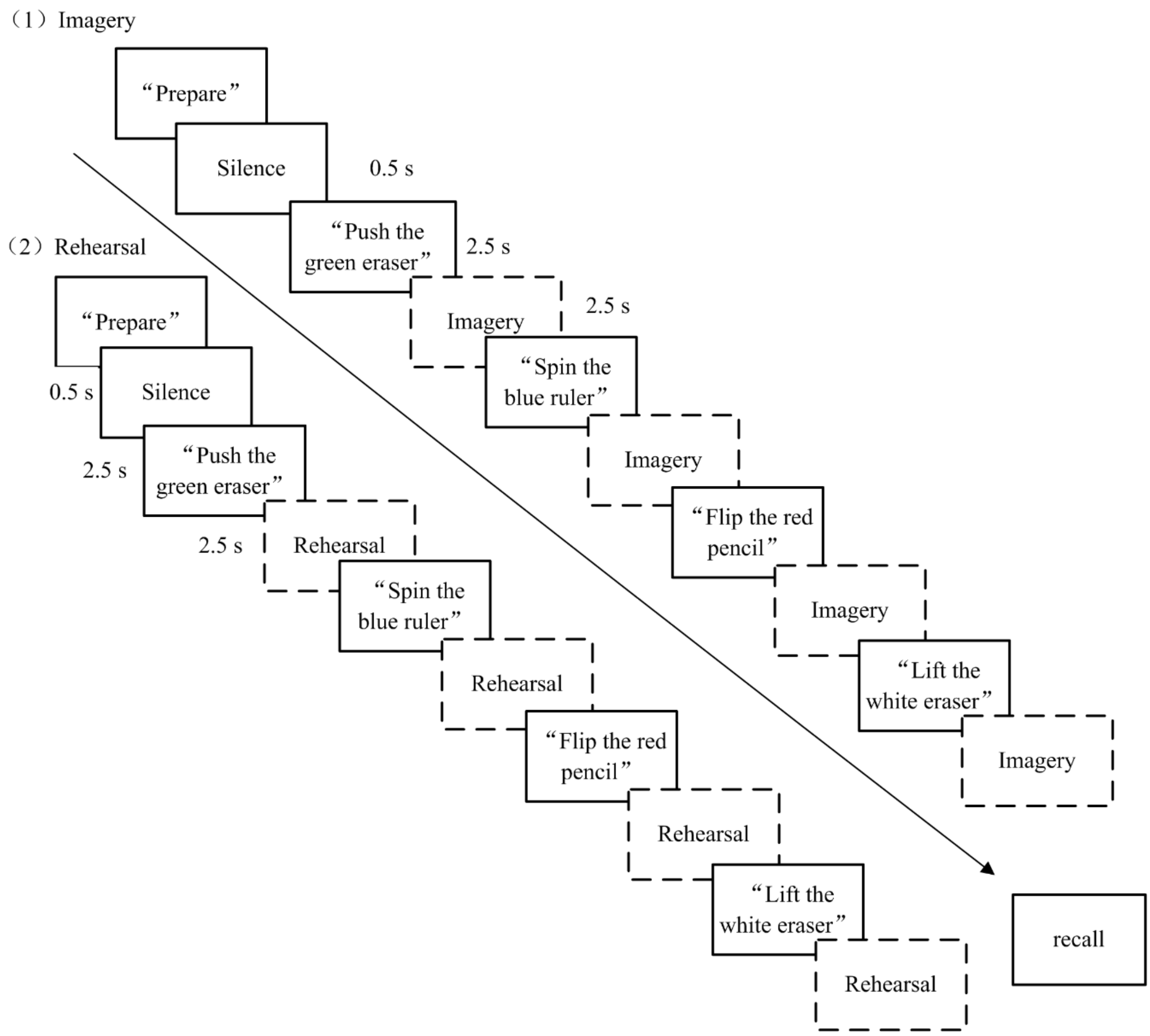

Figure 1. Task diagram showing a trial with four action-object pairs in two types of encoding conditions (imagery and rehearsal). In the task, the oral instructions are presented in Chinese.

The task contained three rules for children: 1) they must put their hands on their lap before the start of each trial; 2) they must not touch the objects before the recall phase; 3) they must recall the instructions in the correct order, and if they forgot any objects or actions in the sequence they must say ‘blank’ for any items that they forgot during recall.

Children then began the first condition. Each condition contained four parts: introduction, demonstration, practice, and formal test. First, the experimenter introduced the requirement of the particular condition. In the rehearsal conditions, children were told to repeat the action-object pair quietly to themselves. In the imagery conditions, they were required to imagine themselves performing the action-object pair in their mind. Second, the experimenter demonstrated the procedure using an example trial (‘pull the white eraser, push the yellow ruler’), and asked the children to do the same. In repetition conditions, the experimenter repeated each action-object pair after it was played, and then recalled the entire sequence after the beep. Children quickly learnt to quietly repeat each action-object pair during the encoding stage. In the imagery conditions, the experimenter verbally described how they used motor imagery strategy, in order to help the children understand how to utilize this strategy. For instance, after the first action-object pair, the experimenter said, ‘In my mind, I imagine my hand moves away from lap, stretches towards the white eraser, takes hold of the white eraser and pulls it towards me, and the white eraser leaves the previous location and moves toward me’. Third, for each condition, children were given two practice trials. Finally, in order to make sure that the children were able to use motor imagery properly, children were asked about the degree and clarity of their motor imagery for the practice trials. If the children reported difficulty with the motor imagery process, they were given more practice. Approximately one third of children required extra practice (this was similar across three age groups). Preliminary statistical analysis showed that there was no difference between children who required further practice, and those that did not, on recall performance in the main task (*ps* > 0.10). During practice, any behavior that broke the rules was corrected (e.g., touching objects when listening to the instructions) until the child could understand the test procedure without occurrence of any rule-breaking behaviors.

After the practice session, the formal test began. Children were told that the instructions would start with sequences of two action-object pairs. Children were always informed about the number of action-object pairs before moving on to the next block, and they always progressed through all blocks, regardless of performance level. Sequence lengths of 2-4 action-object pairs per sequence were used to ensure sensitive performance levels across age groups and conditions (see also Waterman et al., 2017). After completion of all 12 trials in the first test condition, children were given a two-minute break and then moved onto the second test condition, and so forth until they completed all four testing conditions (imagery-verbal recall, imagery-enacted recall, rehearsal-verbal recall, rehearsal-enacted recall). At the end of the test, the experimenter asked the child, ‘When you were listening to the instructions, which way was more helpful for you to remember the instructions? Imagining performing the instructions or repeating the instructions quietly to yourself?' and the answer was recorded (see Appendix A for details of the instruction span task).

Procedure

The study was approved by the ethics committee of an Institute in China. All children completed four sessions across one week, with the first three sessions including tests for other research project. In the final session, children completed the instruction span task.

Results

All outcomes were analyzed using classical and equivalent Bayesian analyses using SPSS 21.0 and JASP 0.11.1 (https://jasp-stats.org/). For ANOVA outcomes, the Bayes Factor (BF_{10}) corresponds to the strength of evidence for the inclusion (i.e. $BF_{incl)}$ of each factor and interaction in the model, across matched models. For follow-up comparisons, BF_{10} are reported, indicating the evidence for the presence of an effect in each case. Bayes factors provide an estimation of the strength of evidence for the data under the null or alternative hypotheses. Although they should be viewed as a continuous rather than a categorical outcome variable, Bayes Factors between 1-3 are typically interpreted as providing weak or anecdotal evidence, with 3-10 representing moderate evidence, and > 10 indicating strong evidence for an effect (Jeffreys, 1961; Wagenmakers et al., 2018).

Action-object pairs

Proportion correct in recall of action-object pairs as a function of encoding strategy, recall modality and age groups is represented in Figure 2, with mean performance collapsed across age groups in Table 1. A 2 (encoding strategy: imagery vs. rehearsal) × 2 (recall modality: verbal vs. enacted) × 3 (age group: 7-8, 9-10, 11-12) repeated ANOVA indicated a significant main effect of encoding strategy ($F_{(1,143)}$=58.08, *MSE*=.01, p<.001, η_p^2=.29, BF_{10}>10,000), with superior performance in the imagery condition compared with the rehearsal condition. There was also a significant main effect of recall modality ($F_{(1,143)}$=175.71, *MSE*=.01, p<.001, η_p^2=.55, BF_{10}>10,000), with better performance in the enacted recall condition compared with the verbal recall condition. The age effect was also significant ($F_{(2,143)}$=26.04, *MSE*=.01, p<.001, η_p^2=.27, BF_{10}>10,000), and planned contrasts indicated a significant linear trend of growth (p<.001, BF_{10}>10,000).

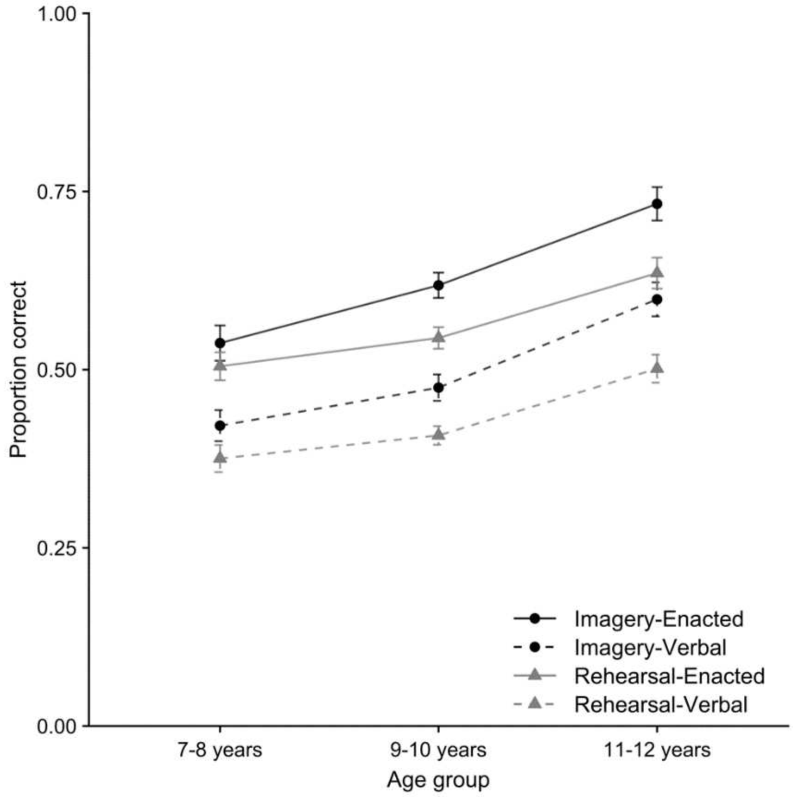

Figure 2. Proportion correct of action-object pairs (with standard errors) as functions of age groups and conditions.

Table 1

Proportion correct in recall of action-object pairs, actions, and objects

	Verbal recall		Enacted recall	
	Imagery	Rehearsal	Imagery	Rehearsal
Action-object pairs	0.49 (0.16)	0.42 (0.12)	0.63 (0.17)	0.56 (0.14)
Actions	0.61 (0.15)	0.55 (0.12)	0.70 (0.15)	0.63 (0.13)
Objects	0.78 (0.16)	0.76 (0.15)	0.84 (0.13)	0.82 (0.12)

The interaction between encoding strategy and recall modality was not significant ($F_{(1,143)}$=0.02, MSE<.01, p=.880, η_p^2<.01, BF_{10} = .12). The interaction between age and encoding strategy was marginally non-significant, showing as a trend for increasing benefit of motor imagery over verbal rehearsal as age increased ($F_{(2,143)}$=2.99, MSE=.01, p=.053, η_p^2=.04, BF_{10}=.65), though the Bayes Factor was weakly supportive of the null. The interaction between age group and recall modality was not significant ($F_{(2,143)}$= 0.28, MSE=.01, p=.756, η_p^2< .01, BF_{10}=.05). The three-way interaction was not significant ($F_{(2,143)}$= 0.17, MSE<.01, p=.842, η_p^2<.01, BF_{10}=.07).

Features: actions and objects

Proportion correct in recall of actions and objects as a function of encoding strategy, recall modality and age groups is represented in Figure 3, with mean performance collapsed across age groups in Table 1.

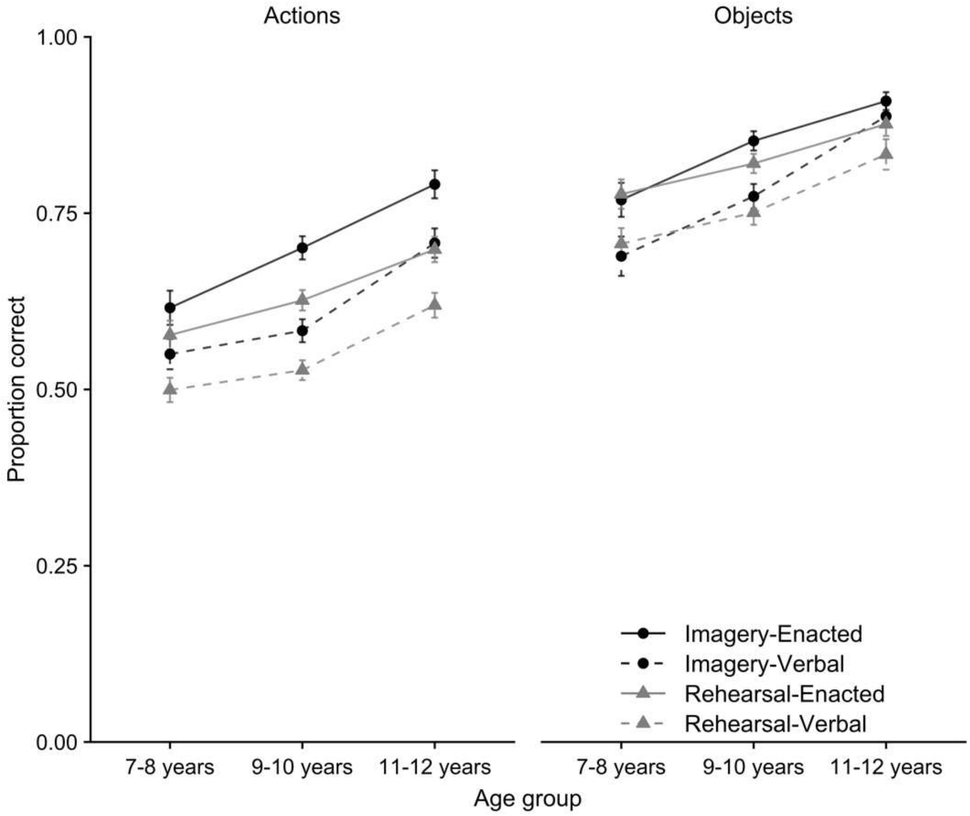

Figure 3. Proportion correct of features (with standard errors) as functions of age groups and conditions.

A 2 (encoding strategy: imagery vs. rehearsal) × 2 (recall modality: verbal vs. enacted) × 2 (feature type: actions vs. objects) × 3 (age group: 7-8, 9-10, 11-12) repeated ANOVA was conducted. We report the results of this analysis focusing on the findings relating to feature type. The main effect of feature type was significant ($F_{(1,143)}$=1032.67, *MSE*=.01, p<.001, η_p^2=.88, BF_{10} > 10,000), showing superior recall of objects compared with actions.

Feature type significantly interacted with encoding strategy ($F_{(1,143)}$=29.95, MSE=.01, p<.001, η_p^2=.17, BF_{10}=180), and the simple effect analysis indicated a medium-sized benefit of motor imagery for memory of actions ($t_{(145)}$=7.44, p<.001, d=.61, BF_{10}>10,000), in contrast to a small advantage of motor imagery for memory of objects that was not well supported by the Bayes Factor ($t_{(145)}$=2.22, p=.023, d=.20, BF_{10}=1.88). Feature type also interacted with recall modality ($F_{(1,143)}$=8.48, MSE<.01, p=.004, η_p^2=.06, BF_{10}=1.60), though this was not well supported by Bayesian analysis. The simple effect analysis indicated a slightly larger enacted recall advantage for actions ($t_{(145)}$=8.60, p<.001, d=.79, BF_{10}>10,000) compared with objects ($t_{(145)}$=6.78, p<.001, d=.50, BF_{10}>10,000). Feature type did not interact with age group ($F_{(2,143)}$=0.556, MSE=.01, p=.326, η_p^2=0.02, BF_{10}=.06), and the three- and four- way interactions were not significant (ps<.05, BF_{10}<.22).

Encoding strategy

Overall, 52.1% children reported the verbal rehearsal strategy as being more helpful for remembering instructions, and 47.9% children reported imagining the instructions as being more beneficial. The type of preferred strategy varied with age (see Figure 4, χ^2=6.66, p=.036, BF_{10} = 1.65), though this was only a small effect overall, and not well supported by the Bayes factor. Nevertheless, it appears that younger children were more likely to express a preference for motor imagery over rehearsal strategy, whereas older children showed the opposite pattern.

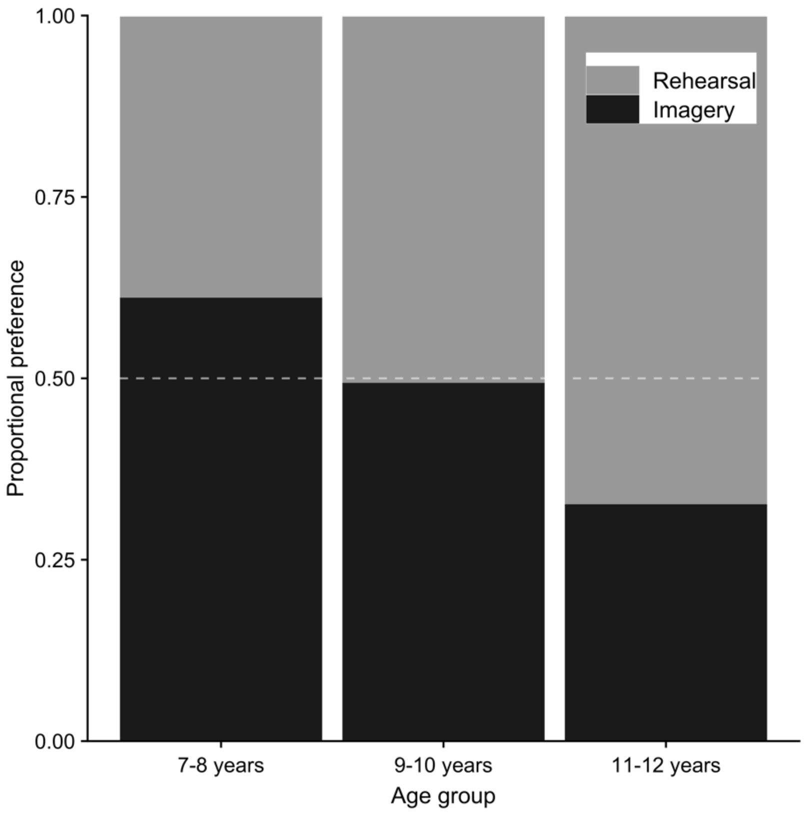

Figure 4. Preference of encoding strategy as a proportion of each age group

Next, we tested whether children's preference for a particular encoding strategy would be linked to their performance, showing as higher performance in rehearsal conditions than imagery conditions in children who preferred a verbal rehearsal strategy and vice versa. The proportion correct of action-object pairs in the two *rehearsal* conditions were averaged, yielding a score as an estimation for performance in rehearsal conditions. Similarly, a score for performance of *imagery* conditions was also calculated. A 2 preference type (rehearsal vs imagery) × 2 encoding strategy (rehearsal vs imagery) ANOVA on action-object pairs showed a main effect of encoding strategy($F_{(1,144)}$=59.76, MSE=.35, p<.001, η_p^2=0.29, BF_{10}>10,000), but no significant effect of preference type ($F_{(1,144)}$=1.103, MSE=.03, p=.295, η_p^2<0.01, BF_{10}=.35) and no significant interaction ($F_{(1,144)}$=0.72, MSE<.01, p=.399, η_p^2< .01, BF_{10}=0.29), indicating that performance did not vary with the type of preferred strategy in children.

Discussion

The present study compared two encoding strategies - verbal rehearsal and motor imagery - in a following instruction working memory task in children from age 7 to 12 years. With increasing age, the ability to follow instructions improved linearly. In all age groups, children had superior recall performance when they imagined performing the instructions during encoding, compared with verbally repeating the instructions during encoding. The size of the motor imagery benefit was similar for both verbal and enacted recall.

The finding that there is a facilitative effect of motor imagery on following instructions is consistent with the hypothesis based on the enacted-recall advantage, providing more evidence for the superiority of a working memory representation generated by action planning/motor imagery compared with verbal representation supported by rehearsal (Jaroslawska et al., 2018; Yang et al., 2016). This finding extends the benefit of motor imagery in long-term memory of action pairs (Ecker & Engelkamp, 1995) to remembering a series of action-object commands within the working memory paradigm.

In addition, when looking at actions and objects separately, the benefit of motor imagery over verbal rehearsal was larger for actions, relative to memory for objects. This is similar to the finding of a recent study investigating the benefit of self-performing compared with observing others' performing following spoken instructions (Allen et al., 2019). In that study, at encoding young adults either viewed videos of demonstrated action-object instruction sequences or performed the instructions themselves, in addition to listening to the instructions. Observing other-enactment at encoding boosted recall for action-object pairs and for actions, but not for objects. Further, Allen et al. (2019) found that self-enactment at encoding had a more limited boost to recall, and suggested that observing others' demonstration of actions is a more effective way to improve memory of spoken instructions, compared with self-enactment, as it is less cognitively demanding for both young adults (Allen et al., 2019) and children (Waterman et al., 2017).

In a similar way to observing others' performance, utilizing motor imagery may reduce the cognitive cost of actually carrying out the action during encoding, but still provide additional spatial-motoric codes to improve recall. Reducing the cognitive cost of implementing a strategy is particularly important for children, given their more limited cognitive resources and reduced working memory capacity relative to adults (Waterman et al, 2017). Future research could directly compare the effect of the three forms of enactment (i.e., observation, self-performing, and imagining performing) in following instructions in children.

The limited effect of imagery on the recall of objects could be explained by the strategies that children might use for memorizing object information. Given the objects are present and visible throughout the test, children may engage in visual tracking of the objects as they hear the object names being read aloud, in order to offload the requirement to maintain the objects in working memory (see also Berry, Allen, Mon - Williams, & Waterman, 2019). This idea is supported by the fact that young adults report the use of a visual-tracking strategy in following spoken instructions (Yang et al., 2016), and by the observation of gaze-based rehearsal behavior of school-age children in a serial spatial memory task (Morey, Mareva, Lelonkiewicz, & Chevalier, 2018). Visual tracking of objects may be used in both verbal rehearsal and motor imagery conditions and may help form a spatial map of the to-be-performed actions. Therefore, it is possible that information relating to objects in the verbal rehearsal conditions may also be maintained in visuospatial forms, which may leave little room for further improvement from motor imagery. This is supported by the superior memory of objects in the present study when compared with memory for actions. It also fits with recent findings suggesting that observing demonstration of instructions during encoding primarily boosts young adults' action (rather than object) memory when objects are visible in the environment, while improving memory for both actions and objects when they are not visually available (Allen et al., 2019).

As well as finding that motor imagery boosts recall, this study also replicated the enacted-recall advantage found in previous studies with developmental groups (Gathercole et al., 2008; Jaroslawska et al., 2016; Waterman et al., 2017; Yang et al., 2017). Moreover, encoding strategy did not interact with recall modality, suggesting that the benefit of using motor imagery and the enacted-recall advantage were additive. It has been argued that the enacted recall advantage reflects the formation of spatial-motoric plans at encoding for later enactment, forming a richer and more robust representation in both children (Gathercole et al., 2008; Jaroslawska et al., 2016; Waterman et al., 2017; Yang et al., 2017) and young adults (Allen & Waterman, 2015). The additive impacts of imagery and enactment found in the present study might be captured by viewing the four conditions (running from rehearsal/verbal recall up to imagery/enactment) as representing escalating involvement of visuospatial-motor planning, with each condition encouraging a greater use of such coding, and resulting in improved performance in each case. This account retains the locus of these effects at the encoding phase, in line with other evidence suggesting that it is the encoding context that produces the enacted recall advantage (e.g. Allen & Waterman, 2015; Jaroslawska et al., 2018; Koriat et al., 1990). Other research involving young adults has suggested that the enacted-recall advantage may also reflect improved retrieval efficiency, emerging as faster speeds in initiating and completing enactment than verbal recall, which may in turn decrease loss of memory during recall (Yang et al., 2019).

The second purpose of the present study was to delineate the developing course of the ability to follow spoken instructions from age 7 to 12 years. Overall, the ability to follow instructions showed a linear improvement across the three age groups. That is, with increasing age, we see improvements in children's memory for sequences of action-object commands. Moreover, all age groups (from age 7 to 12 years) benefited from using the motor imagery strategy compared with verbal rehearsal for maintaining verbal sequence of instructions, and the benefit was consistent across the different age groups. This provides novel evidence that children as young as age 7 can utilize a motor imagery strategy when explicitly instructed to do so, when completing a following instructions task in working memory. The finding is also consistent with literature showing that children by age 7 can use rehearsal strategy to maintain verbal information (Gathercole, 1998; Tam et al., 2010). It also fits with Miller et al (2015) who found that children as young as 5 years old appeared to benefit from exposure to verbal and imagery-based strategies during a short-term memory task. Future studies may examine whether younger children (e.g., 5 to 6 years old) would also display a benefit of motor imagery relative to verbal rehearsal, and whether the benefit would be smaller when compared with older children.

After completion of the following instruction task, children were asked to report which strategy (verbal rehearsal or motor imagery) was more helpful for remembering the instructions. Interestingly, the younger children tended to report that a motor imagery strategy was more helpful compared with verbal rehearsal, whereas the older children showed the opposite pattern, despite all age groups showing a motor imagery benefit in task performance. This finding is unlikely to be explained by differences in metacognitive awareness, as children aged 7 to 8 years old have less well-developed metacognition than children aged 11 to 12 years old (Flavell, 1999; Kuhn, 2000; Schneider, 2008). One possibility is that this finding reflects a *preference* for certain types of strategy, rather than the ability to accurately reflect on which strategy aided performance. This conjecture is supported by the finding that preference of strategy was not linked to actual performance; that is, the group of children who indicated a preference for rehearsal strategy also showed higher performance in the imagery compared with the rehearsal conditions. Previous research has shown that children over the age of 8 years old, like adults, start to show a preference for verbal recoding of visual stimuli, whereas younger children tend to rely on visuospatial working memory when encoding and retrieving visual stimuli (Hitch, Halliday, Schaafstal, & Schraagen, 1988; Miles, Morgan, Milne, & Morris, 1996; Palmer, 2000). The instruction span task in the present study involved visual stimuli (objects), and so the younger children may have a preference for strategies that do not involve verbal recoding (Hitch et al, 1988). However, this novel finding would need replicating before any firm conclusions can be drawn. It would also be useful to explore whether encoding preference changes with recall modality, as children (and adults) may shift their preferred encoding strategy depending on how sequences are to be recalled.

In the present study, we did not investigate whether explicitly using a motor imagery strategy is superior to a baseline condition where children are not instructed which strategy to use. In this situation, children may automatically use both verbal and motor imagery strategies, or not apply any encoding strategy, or use a different type of strategy, which can be difficult to disentangle. Moreover, we cannot completely rule out the possibility that some children might also have imagined performing the sequences whilst engaging in verbal rehearsal, and vice versa. Another possible limitation is that, because the paradigm adopted in the present study was focused on comparing imagery vs. rehearsal of each action-object pair in turn, it does not allow for cumulative rehearsal. This cumulative rehearsal may be more effective for maintaining a series of spoken commands, although it can also lead to increased repetition errors (Lewandowsky & Oberauer, 2015). Finally, the benefit of motor imagery over verbal rehearsal may also reflect the impact of recoding processes; it could be useful to investigate whether recoding (via verbal rehearsal) serves to improve children's ability to follow visually demonstrated instructions. Future work should therefore look to examine the optimal methods of encoding and maintaining instruction sequences using different forms of encoding strategy.

In conclusion, the present study compared two encoding strategies in a following-instructions working memory task in school-aged children. Compared with a verbal rehearsal strategy, motor imagery (imagining acting out the instructions) during encoding led to better recall of instructions. This motor imagery benefit was similar for verbal and enacted recall, as well as for younger and older children. These findings may have implications for educational settings. When children have to follow sequences of instructions, there may be some benefit to encourage children to imagine themselves acting out the instructions as they are listening to them. For example, when children are asked to carry out a sequence of actions in practical lessons such as Design & Technology, or where children have to complete a series of tasks that involves interacting with physical resources in the classroom (e.g., 'put your math book in your desk, put your pencil in the pencil tray, get your reading book from the bookshelf, and go and sit in the library corner'). Future research would need to explore whether this effect is found using more ecologically valid tasks and could further investigate whether allowing gaps between the different instructions within a sequence leads to improved performance compared with giving full instruction without gaps. In addition, it would be useful to investigate whether the benefit of motor imagery over verbal rehearsal remains over longer delays, as is commonly required in everyday learning situations, which could help improve understanding of the maintenance processes of motor and verbal representations.

References

Allen, R. J., Hill, L. J. B., Eddy, L., & Waterman, A. (2019). Exploring the effects of demonstration and enactment in facilitating recall of instructions in working memory. *Memory and Cognition*. doi: 10.3758/s13421-019-00978-6

Allen, R. J., & Waterman, A. H. (2015). How does enactment affect the ability to follow instructions in working memory? *Memory & Cognition, 43*(3), 555-561. doi: 10.3758/s13421-014-0481-3

Annett, J. (1995). Motor imagery: Perception or action? *Neuropsychologia, 33*(11), 1395-1417. doi: 10.1016/0028-3932(95)00072-B

Baddeley, A. D. (1986). *Working Memory*. Oxford: Oxford University Press.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Science, 4*(11), 417-423. doi: 10.1016/S1364-6613(00)01538-2

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2020). A multicomponent model of working memory. In R. H. Logie, V. Camos & N. Cowan (Eds.), *Working memory: State-of -the science.* Oxford: Oxford University Press.

Berry, E. D. J., Allen, R. J., Mon‐Williams, M., & Waterman, A. H. (2019). Cognitive offloading: Structuring the environment to improve children's working memory task performance. *Cognitive Science, 43*(8), e12770-n/a. doi: 10.1111/cogs.12770

Caeyenberghs, K., Tsoupas, J., Wilson, P. H., & Smits-Engelsman, B. C. M. (2009). Motor imagery development in primary school children. *Developmental Neuropsychology, 34*(1), 103-121. doi: 10.1080/87565640802499183

Decety, J., & Grèzes, J. (1999). Neural mechanisms subserving the perception of human actions (Vol. 3, pp. 172-178). LONDON: Elsevier Ltd.

Ecker, W., & Engelkamp, J. (1995). Memory for actions in obsessive-compulsive disorder. *Behavioural and Cognitive Psychotherapy, 23*(4), 349-371. doi: 10.1017/S1352465800016477

Flavell, J. H. (1999). Cognitive development: Children's knowledge about the mind. *Annual Review of Psychology, 50*, 21-45. doi: 10.1146/annurev.psych.50.1.21

Gathercole, S. E. (1998). The development of memory. *Journal of Child Psychology and Psychiatry, 39*(1), 3-27. doi: 10.1111/1469-7610.00301

Gathercole, S. E., & Alloway, T. P. (2008). *Working memory and learning: A guide for teachers.* London: SAGE Publications.

Gathercole, S. E., Durling, E., Evans, M., Jeffcock, S., & Stone, S. (2008). Working memory abilities and children's performance in laboratory analogues of classroom activities. *Applied Cognitive Psychology, 22*, 1019–1037. doi: 10.1002/acp.1407

Hétu, S., Grégoire, M., Saimpont, A., Coll, M.-P., Eugène, F., Michon, P.-E., & Jackson, P. L. (2013). The neural network of motor imagery: an ALE meta-analysis. *Neuroscience and Biobehavioral Reviews, 37*(5), 930-949. doi: 10.1016/j.neubiorev.2013.03.017

Hitch, G. J., Halliday, S., Schaafstal, A. M., & Schraagen, J. M. C. (1988). Visual working memory in young children. *Memory & Cognition, 16*(2), 120-132. doi: 10.3758/BF03213479

Jaroslawska, A. J., Gathercole, S. E., Allen, R. J., & Holmes, J. (2016). Following instructions from working memory: Why does action at encoding and recall help? *Memory and Cognition*. doi: 10.3758/s13421-016-0636-5

Jaroslawska, A. J., Gathercole, S. E., & Holmes, J. (2018). Following instructions in a dual-task paradigm: Evidence for a temporary motor store in working memory. *Quarterly Journal of Experimental Psychology, 71*(11), 2439-2449. doi: 10.1177/1747021817743492

Jaroslawska, A. J., Gathercole, S. E., Logie, M. R., & Holmes, J. (2015). Following instructions in a virtual school: Does working memory play a role? *Memory and Cognition*. doi: 10.3758/s13421-015-0579-2

Jeffreys, H. (1961). *Theory of probability* (3rd ed.). Oxford, UK: Oxford University Press.

Koriat, A., Ben-Zur, H., & Nussbaum, A. (1990). Encoding information for future action: Memory for to-be-performed tasks versus memory for to-be-recalled tasks. *Memory & Cognition, 18*(6), 568-578. doi: 10.3758/BF03197099

Kuhn, D. (2000). Metacognitive development. *Current Directions in Psychological Science, 9*(5), 178-181. doi: 10.1111/1467-8721.00088

Lewandowsky, S., & Oberauer, K. (2015). Rehearsal in serial recall: An unworkable solution to the nonexistent problem of decay. *Psychological Review, 122*(4), 674-699. doi: 10.1037/a0039684

Li, G., Allen, R. J., Hitch, G. J., & Baddeley, A. D. (under review). *Translating words into actions in working memory: the role of spatial-motoric coding*.

Lui, S., Yang, T., Ng, C., Wong, T., Wong, J., Ettinger, U., . . . Chan, R. C. K. (2017). Following instructions in patients with schizophrenia: the benefits of actions at encoding and recall. *Schizophrenia Bulletin, 44*(1), 137-146. doi: 10.1093/schbul/sbx026

Miles, C., Morgan, M. J., Milne, A. B., & Morris, E. D. M. (1996). Developmental and individual differences in visual memory span. *Current Psychology, 15*(1), 53-67. doi: 10.1007/BF02686934

Miller, S., McCulloch, S., & Jarrold, C. (2015). The development of memory maintenance strategies: Training cumulative rehearsal and interactive imagery in children aged between 5 and 9. *Frontiers in Psychology, 6*(MAY), 524. doi: 10.3389/fpsyg.2015.00524

Morey, C. C., Mareva, S., Lelonkiewicz, J. R., & Chevalier, N. (2018). Gaze‐based rehearsal in children under 7: a developmental investigation of eye movements during a serial spatial memory task. *Developmental Science, 21*(3), e12559-n/a. doi: 10.1111/desc.12559

Munzert, J., Lorey, B., & Zentgraf, K. (2009). Cognitive motor processes: The role of motor imagery in the study of motor representations. *Brain Research Reviews, 60*(2), 306-326. doi: https://doi.org/10.1016/j.brainresrev.2008.12.024

Palmer, S. (2000). Working memory: A developmental study of phonological recoding. *Memory, 8*(3), 179-193.

Schneider, W. (2008). The development of metacognitive knowledge in children and adolescents: Major trends and implications for education. *Mind, Brain, and Education, 2*(3), 114-121.

Schuster, C., Hilfiker, R., Amft, O., Scheidhauer, A., Andrews, B., Butler, J., . . . Ettlin, T. (2011). Best practice for motor imagery: A systematic literature review on motor imagery training elements in five different disciplines. *BMC Medicine, 9*(1), 75-75. doi: 10.1186/1741-7015-9-75

Smyth, M. M., & Waller, A. (1998). Movement imagery in rock climbing: Patterns of interference from visual, spatial and kinaesthetic secondary tasks. *Applied Cognitive Psychology, 12*(2), 145-157. doi: 10.1002/(SICI)1099-0720(199804)12:2<145::AID-ACP505>3.0.CO;2-Z

Spruijt, S., van der Kamp, J., & Steenbergen, B. (2015). Current insights in the development of children's motor imagery ability. *Frontiers in Psychology, 6*(787). doi: 10.3389/fpsyg.2015.00787

Tam, H., Jarrold, C., Baddeley, A. D., & Sabatos-DeVito, M. (2010). The development of memory maintenance: Children's use of phonological rehearsal and attentional refreshment in working memory tasks. *Journal of Experimental Child Psychology, 107*(3), 306-324.

Wagenmakers, E. J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., . . . Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychon Bull Rev, 25*(1), 58-76. doi: 10.3758/s13423-017-1323-7

Waterman, A. H., & Allen, R. J. (2019). *Following instructions: the effect of 'imagining' on recall*. Paper presented at the Working Memory Meeting, Yorkshire, UK.

Waterman, A. H., Atkinson, A. L., Aslam, S. S., Holmes, J., Jaroslawska, A., & Allen, R. J. (2017). Do actions speak louder than words? Examining children's ability to follow instructions. *Memory & Cognition*, 1-14. doi: 10.3758/s13421-017-0702-7

Wojcik, D. Z., Allen, R. J., Brown, C., & Souchay, C. (2011). Memory for actions in autism spectrum disorder. *Memory, 19* (6), 549-558. doi: 10.1080/09658211.2011.590506

Wolpert, D. M. (1997). Computational approaches to motor control. *Trends In Cognitive Sciences, 1*(6), 209-216. doi: 10.1016/S1364-6613(97)01070-X

Yang, T., Allen, R. J., & Gathercole, S. E. (2016). Examining the role of working memory resources in following spoken instructions. *Journal of Cognitive Psychology, 28*(2), 186-198. doi: 10.1080/20445911.2015.1101118

Yang, T., Allen, R. J., Holmes, J., & Chan, R. C. K. (2017). Impaired memory for instructions in children with attention-deficit hyperactivity disorder is improved by action at presentation and recall. *Frontiers in Psychology, 8*(39). doi: 10.3389/fpsyg.2017.00039

Yang, T., Allen, R. J., Yu, Q., & Chan, R. C. K. (2015). The influence of input and output modality on following instructions in working memory. *Scientific Reports, 5*. doi: 10.1038/srep17657

Yang, T., Gathercole, S. E., & Allen, R. J. (2014). Benefit of enactment over oral repetition of verbal instruction does not require additional working memory during encoding. *Psychon Bull Rev, 21*(1), 186-192. doi: 10.3758/s13423-013-0471-7

Yang, T., Jia, L., Zheng, Q., Allen, R. J., & Ye, Z. (2019). Forward and backward recall of serial actions: Exploring the temporal dynamics of working memory for instruction. *Memory & Cognition, 47*(2), 279-291. doi: 10.3758/s13421-018-0865-x

Appendix A

The instruction span task (strategy implementation version)

1. Task setting and overall introduction

The experimenter prepared the computer and recording sheets, and placed the objects as shown in Figure A1. The location of the objects remained the same throughout the test.

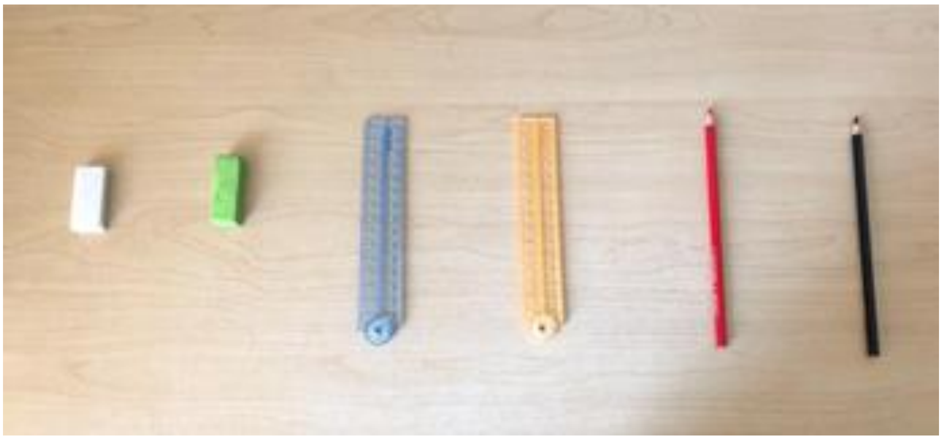

Figure A1. Display of objects on a desktop

The child sat at the desk facing the objects, with the chair adjusted to a comfortable height, and all the objects within arm’s reach. The experimenter sat behind and to the side of the child. The experimenter set the volume of audio to be suitable for the child.

2. Practice of naming objects

The experimenter said, 'We are going to play a memory game, so now let us get familiar with these items first. The objects include a white eraser, a green eraser, a blue ruler, a yellow ruler, a red pencil, and a black pencil. Now please tell me the name of these objects from left to right.' If the child provided an incorrect answer, the experimenter corrected it immediately and required the child to name it again until all the names of objects were provided correctly.

3. Practice of the actions

The experimenter said, 'Next, let us get familiar with the actions.' The experimenter demonstrated each action while speaking the names (*push, pull, spin, tap, lift, flip*). Six action-object pairs were provided (*push the white eraser; pull the green eraser; spin the blue ruler; tap the yellow ruler; lift the red pencil; flip the black pencil*).While speaking the action *push*, *pull*, and *lift*, the experimenter moved the object approximately 5 cm away from the original position. For the action *tap*, the experimenter patted the object from above. For the action *flip*, the experimenter picked up the object and turned it upside down. For the action *spin*, the experimenter rotated the object clockwise by 45 degrees (only for demonstration, the exact rotation angle was not required in the formal test). After demonstration, the experimenter said, 'Now, I will do each action and you tell me the name of the action.' The experimenter then performed each action one at a time and the child gave the name of the action, any inaccurate answer was immediately corrected by the experimenter. Finally, the experimenter said, ‘Next, I will say the names of the actions, and you do the actions.’ The experimenter needed to check whether the child could understand and operate the actions correctly and smoothly, as well as checking that the six types of actions were distinguishable. The details of the movement such as the distance of movement and the angle of rotation were not strictly required to be exactly the same as the experimenter’s demonstration. Any mistake when performing actions during practice was immediately corrected by the experimenter.

4. Introduction of the task

The experimenter explained the overall task requirements to the child. The experimenter said, ‘Now, let me introduce the rules of the game. You will hear spoken instructions played on the computer. Each instruction contains a series of action-object pairs such as *pull the white eraser*, and *push the yellow ruler*. There are silent pauses between action-object pairs. At the end of an instruction, when you hear a reminding tone *du*, you need to recall the entire instruction in order.’

Next, the experimenter introduced the rules, ‘There are some rules for the task. First, you need to put your hands on your lap before each instruction starts. Second, while the spoken instruction is playing, you need to listen carefully and avoid making any hand movements. Third, you need to remember all the action-object pairs in order as much as possible. If you forget an action-object pair, you say “*blank”* instead. A blank represents a forgotten action-object pair. For example, if the instruction is *pull the white eraser and push the yellow ruler,* and you forget the first action-object pair, you need to say *blank* and *push the yellow ruler*. Now, let's start the first game.' In the formal test, if a child forgot to say *blank*, the experimenter would remind the child after the trial ends.

5. Subtasks

There were four subtasks, namely, rehearsal-verbal recall, rehearsal-enacted recall, imagery-verbal recall, and imagery-enacted recall. The order of the four subtasks were balanced across participants in the study.

Subtask A：Rehearsal-verbal recall condition (introduction and practice)

The experimenter first introduced the task requirement by saying, 'I will play the spoken instructions on my computer. Each instruction contains a series of action-object pairs and there is a silent pause after each one. During this time, you need to *repeat the action quietly*. At the end of the instruction, you will hear the reminding tone *du*, and you need to *speak out* loud all the action-object pairs of the instruction in order.'

The experimenter then demonstrated the procedure, and said, 'I will demonstrate, and you must observe how I perform it.' The experimenter played the sample recording and repeated each action *quietly*, and *repeat*ed the entire instruction after hearing the *du* sound. After the demonstration, the experimenter said, ‘This time, I will play the instructions, and you do the task as I just demonstrated. After each action, you must repeat it quietly, and when you hear the *du* sound, say out loud all the action-object pairs in order. Let’s practice.’ The experimenter played two practice trials, and observed and corrected any rule-breaking behaviors until the child could perform the task as required. The experimenter paid attention to the typical errors that might occur during the encoding stage (e.g., repeating the instructions aloud or silently; pointing to or touching objects; simulating enactment). These rule-breaking behaviors were prohibited by the experimenter.

After the experimenter had ensured the child could understand and perform the task correctly, the experimenter started the formal test. The procedure of the formal test was similar across all four subtasks (see the end of Appendix A).

Subtask B：Rehearsal-enacted recall condition (introduction and practice)

The experimenter first introduced the task requirement by saying, ‘I will play the spoken instructions on my computer. Each instruction contains a series of action-object pairs and there is a silent pause after each one. During this time, you need to *repeat the* action-object pairs *quietly*. At the end of the instruction, you will hear the reminding tone *du*, and you need to *perform* all the action-object pairs of the instruction in order. Please be aware that you can use one hand or both hands to complete the task, but do not use both hands at the same time on the same object.’

The experimenter then demonstrated the procedure, and said: “I will demonstrate, and you must observe how I perform it.’ The experimenter plays the sample recording and *repeats each action quietly*, and *performed* the entire instruction sequentially after the *du* sound. After recall, the experimenter put all the objects back in their initial locations. After the demonstration, the experimenter said, ‘This time, I will play the instructions, and you do as I just demonstrated. After each action, you should repeat it quietly, and when you hear the *du* sound, perform all the action-object pairs in order. Let’s practice.’ The practice procedure was similar to that in Subtask A except for the additional typical error (i.e., placing the object back immediately after enactment in the middle of recalling process). After practice, the formal test began (see the end of Appendix A).

Subtask C：Imagery-verbal recall condition (introduction and practice)

The experimenter first introduced the task requirement by saying, ‘I will play the spoken instructions on my computer. Each instruction contains a series of action-object pairs and there is a silent pause after each one. During this time, you need to *imagine the procedure of completing the action in your mind*. At the end of the instruction, you will hear the reminding tone *du*, and you need to *speak out loud* all of the action-object pairs of the instruction in order.’

The experimenter then demonstrated the procedure, and said, ‘I will demonstrate and describe how I imagine the actions; but in the formal test, you do not need to speak out loud what you are doing'. The experimenter then played the first sample recording *pull the white eraser*, and said 'In my mind, I imagine my hand moves away from lap, stretches towards the white eraser, takes hold of the white eraser and pulls it towards me, and the white eraser leaves the previous location and moves toward me'. The experimenter then played the second sample recording *push the yellow ruler*, and said 'In my mind, I imagine my hand moves away from lap, stretches towards the yellow ruler, takes hold of the yellow ruler and pushes it away from me, and the yellow ruler leaves the previous location and moves away from its previous location'.

After this demonstration, the experimenter said, 'This time, I will play the instructions, and you do as I just demonstrated. Please try to imagine the process of completing the action after hearing it. You don't need to speak out loud what you are doing as I just demonstrated, just imagining it in your head is fine. When you hear the *du* sound, *speak out* all the action-object pairs in order'. The experimenter then played the two practice trials (same as demonstrations). After the child recalled the instructions, the experimenter asked, 'To what extent do you think you can imagine the actions in the instruction?' then the child selected from the following options (1=cannot imagine the actions at all; 2=have difficulty imagining the actions; 3=can imagine the actions a little; 4=can imagine the actions quite a lot; 5=can imagine the actions completely). If the child reported difficulty with motor imagery (option 1 or 2), the child had further motor imagery practice with eyes closed, or speaking out loud as they engaged in the imagery process. In the formal test, all children were required to imagine the actions silently with eyes open.

After that, the experimenter said, ‘Let’s have some more practice.’ Similar to subtask A, the experimenter played two practice trials, and observed and corrected any rule-breaking behaviors until the child could perform the task as required. After practice, the experimenter asked, ‘When you were imagining the actions, how clearly could you see those actions in your head?’ then selected from the following options (1= very vague; 2 = quite vague; 3= average; 4= clear; 5=very clear), and recorded the answer. The formal test then began (see the end of Appendix A).

Subtask D：Imagery-enacted recall condition (introduction and practice)

The experimenter first introduced the task by saying, ‘I will play the spoken instructions on my computer. Each instruction contains a series of action-object pairs and there is a silent pause after each one. During this time, you need to *imagine the procedure of completing the action in your mind*. At the end of the instruction, you will hear the reminding tone *du*, and you need to *perform* all of the action-object pairs of the instruction in order. Please be aware that you can use one hand or both hands to complete the task, but do not use both hands at the same time on the same object.’

After that, the experimenter demonstrated motor imagery, with the process being the same as that described in subtask C. Given the counterbalancing of subtasks across participants, the experimenter only needed to demonstrate motor imagery technique in the first motor imagery condition and skipped this process in the second motor imagery condition.

Then, the experimenter repeated the requirements of the task, and asked children to practice. The practice process was similar to subtask C, including two trials and the question about the clarity of motor imagery. The formal test then began (see the end of Appendix A).

6. Instruction of formal test

The experimenter said, ‘The official game is about to begin, please put your hands on your lap. We will start with the instructions involving two action-object pairs. Are you ready?’ The experimenter said ‘ready’ at the beginning of each instruction trial, and then played the audio recording. Before moving on to the next span, the experimenter always informed the child about the number of action-object pairs by saying ‘The following instructions will contain three/four action-object pairs. Are you ready?’

7. Strategy question

After the child completed all of the subtasks, the experimenter asked, ‘When you were listening to the instructions, which way was more helpful for you to remember the instructions? Imagining performing the instructions or repeating the instructions quietly to yourself?’

The experimenter recorded the answer: ☐ Imagine ☐ Repeat

Appendix B

List1

Span 2

Tap the white eraser, pull the yellow ruler

Flip the blue ruler, push the black pencil

Spin the red pencil, pull the white eraser

Pull the green eraser, tap the yellow ruler

Span 3

Push the yellow ruler, spin the black pencil, lift the blue ruler

Lift the black pencil, pull the red pencil, flip the white eraser

Tap the green eraser, push the blue ruler, flip the yellow ruler

Flip the blue ruler, spin the white eraser, pull the black pencil

Span 4

Push the green eraser, spin the blue ruler, flip the red pencil, lift the white eraser

Pull the blue ruler, push the green eraser, lift the black pencil, tap the red pencil

Lift the white eraser, push the red pencil, tap the green eraser, spin the yellow ruler

Spin the yellow ruler, lift the red pencil, tap the black pencil, flip the green eraser

List 2

Span 2

Spin the blue ruler, tap the green eraser

Pull the red pencil, flip the blue ruler

Tap the yellow ruler, push the red pencil

Pull the white eraser, push the yellow ruler

Span 3

Lift the black pencil, tap the blue ruler, flip the green eraser

Spin the yellow ruler, flip the white eraser, lift the red pencil

Push the blue ruler, pull the green eraser, spin the black pencil

Pull the black pencil, spin the red pencil, flip the blue ruler

Span 4

Lift the black pencil, tap the white eraser, pull the green eraser, flip the red pencil

Tap the yellow ruler, push the white eraser, flip the black pencil, lift the green eraser

Spin the black pencil, lift the blue ruler, pull the yellow ruler, push the white eraser

Lift the white eraser, tap the red pencil, push the green eraser, spin the yellow ruler

List3

Span 2

Pull the black pencil, spin the white eraser

Lift the yellow ruler, push the blue ruler

Push the green eraser, spin the black pencil

Pull the blue ruler, tap the red pencil

Span 3

Pull the white eraser, tap the blue ruler, flip the green eraser

Flip the yellow ruler, tap the green eraser, pull the black pencil

Pull the red pencil, flip the yellow ruler, spin the green eraser

Lift the white eraser, spin the blue ruler, flip the red pencil

Span 4

Tap the black pencil, pull the green eraser, lift the red pencil, push the white eraser

Lift the white eraser, flip the black pencil, push the green eraser, spin the yellow ruler

Spin the blue ruler, lift the red pencil, tap the yellow ruler, push the white eraser

Tap the red pencil, push the yellow ruler, lift the black pencil, flip the blue ruler

List4

Span 2

Tap the green eraser, spin the red pencil

Flip the yellow ruler, push the green eraser

Pull the blue ruler, lift the white eraser

Lift the blue ruler, push the red pencil

Span 3

Pull the yellow ruler, spin the green eraser, tap the white eraser

Tap the black pencil, pull the red pencil, flip the blue ruler

Flip the red pencil, push the yellow ruler, spin the black pencil

Flip the white eraser, spin the yellow ruler, lift the blue ruler

Span 4

Pull the white eraser, tap the black pencil, flip the blue ruler, lift the yellow ruler

Flip the red pencil, push the white eraser, lift the green eraser, spin the black pencil

Spin the green eraser, pull the black pencil, tap the white eraser, push the red pencil

Lift the black pencil, push the green eraser, pull the yellow ruler, tap the blue ruler