How does enactment affect the ability to follow instructions in working memory?

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<u>Abstract</u>

Recent studies examining working memory for sequences of instructions have demonstrated a performance advantage when instructions are physically enacted rather than verbally recalled. However, little is known about the source of this effect, or how instructions are stored in working memory more generally. In particular, no previous studies have compared impacts of enactment on encoding vs. recall in working memory. We conducted an experiment to examine the impact of enactment on both the encoding and recall phases of a task measuring memory for sequences of simple action-object pairs (e.g. *touch the circle, spin the cross, flip the square...*) in young adult participants. An advantage for enacted over verbal recall was observed, in line with recent evidence. In addition, enactment of actions during the encoding phase on each trial significantly facilitated subsequent performance; this effect was particularly apparent for verbal repetition rather than enacted recall. These findings are interpreted as reflecting a beneficial role for spatial-motoric coding in working memory, that can be engaged either through action planning or physical performance.



Keywords: working memory; enactment; following instructions; SPT

How does enactment affect the ability to follow instructions in working memory?

From the classroom to the vocational training course, the ability to retain and subsequently implement sequences of instructions is critical for successful performance. While considerable research has examined this ability in long-term memory tasks, very few studies have explored how this might operate over shorter time periods. This is surprising, given that instructions can often require temporary storage and immediate implementation, and the close links that have been emphasized between working memory and action (e.g. Baddeley, 2012). Indeed, working memory itself can be defined as a limited capacity system that "supports human thought processes by providing an interface between perception, long-term memory and action" (Baddeley, 2003, pp. 829). The current study therefore aimed to explore the cognitive underpinnings involved in retaining and implementing instructional sequences, with a particular focus on how enactment and action planning relate to working memory.

The vast majority of research on working memory has examined simple verbal recall or recognition tests for verbal and visuospatial information. However, the few studies that have been carried out on enactment and working memory suggest that storing instructions for subsequent physical implementation involves factors additional to those involved in verbal repetition. Koriat, Ben-Zurr, and Nussbaum (1990) presented short sequences of action-object pairs involving real objects (e.g. *"touch the stone, lift the ashtray, move the pencil"*) and manipulated whether participants recalled via physical enactment or verbal repetition. It was found that enacted recall was more accurate than verbal recall. In addition, when participants encoded the sequence in anticipation of enacted recall, performance on a surprise verbal test was improved, indicating that the enacted recall advantage at least partly reflects beneficial impacts of action planning

during encoding. More recently, Gathercole, Durling, Evans, Jeffcock, and Stone (2008) examined the ability of 5-6 year old children to either perform or verbally repeat sequences such as "*Pick up the blue ruler and put it in the red folder then touch the green box*", and observed a substantial advantage for enacted over verbal recall. These findings suggest that an imaginal-enactive action plan is constructed when instructional sequences are encountered for later implementation, which can be used to underpin actual performance of the instructions, but may also benefit verbal recall (Koriat et al., 1990).

There is likely to be an important role for working memory resources in instruction storage and action planning (Logie, Engelkamp, Dehn, & Rudkin, 2001; Smyth et al., 1988). For example, Gathercole et al. (2008) found that performance on their instructions task significantly correlated with children's working memory ability. In order to explore this further, Yang, Gathercole, and Allen (2014) examined the involvement of different sub-components of the tripartite working memory model (e.g. Baddeley, 1986) in enacted recall performance and verbal repetition, testing contributions of phonological short-term memory (using articulatory suppression during instruction presentation), spatial processing (using simple spatial tapping), and executive control (backward counting) to memory for visually presented (written) instructions. Each of these manipulations negatively impacted on task performance, indicating roles for the proposed underlying subcomponents in the ability to follow instructions. However, none of these tasks had any impact on the magnitude of the action advantage that was consistently observed. Thus, while working memory is critical to the storage and processing of verbal sequences (see also Baddeley, Hitch, & Allen, 2009), the executive control and modality-specific subcomponents of the tripartite

model (Baddeley, 1986) do not appear to fully capture action planning as indexed by the enacted recall advantage.

Therefore, if these components of working memory are not the source of the action advantage, what other factors might be important in action planning? One potential way to explore this might be provided by encoding-enactment, or the 'subject-performed task' (SPT) manipulation, in which participants enact each instruction during encoding. This should be distinguished from *recall*-enactment, and indeed, it is open to debate whether the cognitive processes involved in actual enactment are exactly equivalent or differ in some respects from those arising from planning for later performance (as studied by Koriat et al., 1990 and others). Enactment at encoding has primarily been explored in the context of long-term memory tasks (involving large numbers of actions and delayed recall), with several studies showing beneficial effects on subsequent verbal recall (e.g. Cohen, 1981; Engelkamp, 1998). While this effect is claimed to be automatic and non-strategic in nature (Cohen, 1981), the form of representation that it provides has been the cause of some debate. Bäckman and Nilsson (1984) suggested that enactment at encoding drives the construction of a visual code that can be used to supplement verbal memory and support later recall. Alternatively, performing each action during instruction might lead to the construction of a motoric (or kinaesthetic) code (e.g. Engelkamp & Zimmer, 1989). In line with this, concurrent performance of unrelated motor tasks has larger effects on later recall than analogous visual interference (e.g. Cohen, 1989; Saltz & Donnenwerth-Nolan, 1981), and motoric similarity between actions disrupts later recognition (e.g. Engelkamp & Zimmer, 1995).

Given effects of self-enactment on long-term verbal recall and recognition tasks, this methodology may provide a productive means of further exploring instruction

memory and action planning in working memory. Few studies have examined the effects of enactment during encoding on working memory performance. Wojcik, Allen, Brown and Souchay (2011) found that, while children with autism spectrum disorder were impaired on the Gathercole et al. (2008) working memory action task (relative to healthy controls), both groups showed improvement in enacted recall performance as a result of earlier enactment during encoding. A similar beneficial effect of encoding-enactment was observed on the immediate verbal recall of instructions in groups of healthy older adults and patients with mild Alzheimer's disease (Charlesworth, Allen, Morson, Burn, & Souchay, 2014). Although this work suggests that an SPT manipulation can boost working memory performance, they do not indicate how enactment at encoding and recall may interact. To date, no previous research has examined the effects of enactment during encoding on enacted vs. verbal recall in working memory. By orthogonally manipulating whether healthy young adult participants physically enact during encoding or during recall, we can obtain novel insights into action planning, motoric processing, and working memory, while also possibly highlighting optimal ways in which instructions should be presented.

This experiment therefore examined the impact of enactment during encoding on immediate enacted recall or verbal repetition of short instructional sequences. During the auditory-verbal presentation of instructions made up of simple action-object pairs, participants either did nothing or enacted each pair in turn, before then attempting to physically enact or verbally repeat the entire sequence. In line with previous findings, we predicted positive effects of enactment at both encoding (Charlesworth et al., 2014; Wocjik et al., 2011) and recall (Gathercole et al., 2008; Yang et al., 2014) in groups of young adult participants. The novel central question is whether and how these forms of

enacted processing might interact; do beneficial effects of enactment during encoding vary in magnitude depending on whether enactment is also required at recall? One possibility is that enactment at encoding provides a larger boost to subsequent action performance than to verbal recall, in keeping with the principle of transfer appropriate processing. Such a prediction assumes that action planning is not fully automatic, and would benefit from the development and strengthening of visual and/or motoric coding that encoding-enactment provides. Alternatively, encoding-enactment might improve verbal recall to a greater extent. For the enacted recall condition, participants may actively construct an action plan incorporating visuo-spatial and motoric coding, and thus would not substantially benefit further from actual enactment during encoding; for verbal recall however, participants may not effectively construct such representations unless 'forced' to through enactment at encoding, therefore showing a larger beneficial effect of this manipulation on recall performance. Such findings would provide insight into the source of the established enacted-recall advantage (Gathercole et al., 2008; Yang et al., 2014) and the cognitive processes underpinning action planning and verbal memory.

*Method*

*Participants*

There were 28 participants (6 males and 22 females, aged 18-22 years) in this experiment. All were undergraduate students at the University of Leeds, had English as their first language, and took part in exchange for course credit.

*Materials*

Based on pilot work, each sequence consisted of five action-object pairs. A pool of eight abstract shapes (star, square, moon, diamond, triangle, heart, circle, hexagon) was used. Each of the five actions in a sequence was drawn from an experimental pool of six (flip, push, drag, spin, touch, lift). Objects and actions were selected without replacement within a sequence (e.g. *drag the hexagon, flip the circle, push the moon, lift the square, touch the diamond*), with 44 sequences used across the experiment. The abstract nature of the stimulus set means that any prior association in semantic memory between a particular object and action is unlikely, thus rendering these pairings truly arbitrary and likely to rely on temporary creation in working memory for their successful recall. Shapes were presented in neutral-colored laminated card form, each measuring approximately 5cm x 5cm.

*Design and Procedure*

The experiment implemented a 2x2 repeated measures design, manipulating encoding condition (no enactment vs. enactment) and response type (verbal vs. action recall). Each condition was performed in a separate block, in counterbalanced order across participants. There was 1 practice trial and 10 test trials in each condition.

Each session started by familiarizing participants with the shapes and their labels, and what each physical action involved. Shapes were placed on the table in front of the participant, in a pseudo-random spatial configuration that remained constant for each participant. Each condition involved auditory-verbal presentation of the instructional sequence. Each sequence was orally presented to the participant at a steady rate, with a pause of approximately three seconds between each action-object pair. For the encoding-enactment conditions, participants carried out each instructional segment during the inter-stimulus interval. For the no enactment during encoding

conditions, participants simply listened to the instructional sequence. Presentation rate and duration were equivalent for all conditions, and shapes remained visible throughout all phases.

The response phase started immediately following the end of the instructional sequence and the final three-second delay. For the Verbal recall condition, participants attempted to verbally recall the entire set of action-object pairs, in their original order. For Enacted recall, participants physically carried out each of the action-object pairs in turn.

<center>*Results*</center>

Responses were scored as correct if actions and objects were recalled in their original pairings, in the correct position in the sequence, with accuracy reported as the mean proportion of action-object pairs correctly recalled[1]. Mean proportion correct in the encoding and recall conditions are displayed in Figure 1, and as a function of serial position in Figure 2. The data were analyzed using a 2x2x5 (encoding condition x response type x serial position) repeated measures ANOVA. This revealed a significant effect of encoding condition, $F(1,28) = 6.99$, $MSE = .06$, $p < .05$, $\eta p^2 = .20$, with a positive effect of enactment during encoding on later recall. The effect of response type was also significant, $F(1,28) = 32.45$, $MSE = .06$, $p < .001$, $\eta p^2 = .54$, with enacted recall more accurate than verbal recall.

The interaction between encoding condition and response type was significant, $F(1,28) = 15.47$, $MSE = .04$, $p = .001$, $\eta p^2 = .37$. Planned comparisons revealed a significant effect of enactment on verbal recall, $t(27) = 5.41$, $p < .001$, *Cohen's d* $= .86$, but not on action performance, $t(27) = .40$ $p = .70$, $d = .07$. Comparing action and verbal recall,

accuracy was higher for action recall both without enactment during encoding, $t$ (27) = 6.63, $p < .001$, $d = .1.14$, and with enactment, $t$ (27) = 3.10, $p < .01$, $d = .39$, although the response type effect size is clearly reduced in the latter condition.

Returning to the omnibus analysis, the effect of serial position was significant, $F$ (4,112) = 90.04, $MSE = .03$, $p < .001$, $\eta p^2 = .76$. A post hoc Tukey test indicated that accuracy at all positions differed from each other ($p < .05$), apart from between positions 3 and 5, and positions 4 and 5, suggesting a strong primacy effect and the absence of a significant recency effect. In addition, a significant encoding condition by serial position interaction was observed, $F$ (4,112) = 3.95, $MSE = .02$, $p < .01$, $\eta p^2 = .12$. Post-hoc Tukey tests indicated that the beneficial effect of enactment during encoding was only significant (at $p < .05$) at sequence positions 4 and 5. There was also a significant interaction between response type and serial position, $F$ (4,112) = 6.57, $MSE = .02$, $p < .001$, $\eta p^2 = .19$. Post hoc Tukey tests indicated significantly higher accuracy for action over verbal recall at each of the 5 serial positions, though the effect was somewhat larger at the final positions. Finally, the three-way interaction between encoding condition, response type, and serial position was not significant, $F$ (4,112) = 1.34, $MSE = .02$, $p = .26$, $\eta p^2 = .05$.

*Discussion*

While considerable research has explored how long-term memory performance is impacted by enactment (e.g. Cohen, 1981; Engelkamp, 1998), few studies have applied this to the immediate recall of short sequences as is typically used in measures of working memory. Such studies (e.g. Gathercole et al., 2008; Koriat et al., 1990; Yang et al., 2014) have focused on enactment during the response phase, and typically used real objects that may have pre-existing associations with movements. In contrast, the current

study is the first to examine the impact of physical enactment performed during both encoding and recall on the ability to follow instructions in working memory. We also used arbitrary pairings of abstract shapes and actions that were repeatedly used in different combinations on every trial, in order to emphasize temporary storage and working memory processing and minimize contributions from long-term memory. We observed a significant recall advantage for enacted over verbal responses, adding to a developing body of evidence indicating that planning for and implementing a set of physical actions facilitates working memory performance (Gathercole et al., 2008; Koriat et al., 1990; Yang et al., 2014). In contrast, the effects of enactment during encoding were dependent on the type of recall required. A beneficial effect of encoding-enactment emerged, but this effect was much larger and indeed only significant for verbal rather than enacted recall, a finding that runs contrary to predictions based on transfer appropriate processing. Thus, physical enactment during encoding particularly facilitates working memory when participants are preparing for verbal repetition rather than planning for enacted recall. This pattern of findings somewhat resembles those observed in LTM recognition (Freeman & Ellis, 2003), suggesting actual enactment during encoding and planning for enactment at a later point in time to be non-additive in nature. Analysis of performance across serial positions indicated that enactment effects were larger at later positions in the sequence, and indeed, enactment at encoding only facilitated verbal recall at later positions. This would indicate that, while retention of the initial parts of a sequence may have a stronger verbal element (via storage in the phonological loop), this capacity is soon exceeded. Our study suggests that availability of additional forms of coding as provided by enactment would then become particularly useful in supporting ongoing performance.

What additional processes or representational formats might contribute to these effects? One possibility is that sensori-motor information is incorporated into the memorial representation, increasing its distinctiveness and accessibility (Freeman & Ellis, 2003; Logie et al., 2001; Zimmer, Helstrup, & Engelkamp, 2000). Thus, when planning for enactment-based recall, participants may actively build a representation that includes visuospatial and motoric information, possibly incorporating representations of intended actions (see Frith, Blakemore, & Wolpert, 2000). This would result in richer forms of coding that produce superior recall relative to verbal repetition. Actual enactment during initial instruction will not particularly add to this. However, it does boost verbal recall, by forcing participants to generate these additional forms of coding that may not otherwise be constructed. This account would also imply that spatial-motoric codes are not spontaneously generated whenever instructions are encountered, even though they can be beneficial to memory performance. Our study supports this idea, but further experimentation will be required to establish the conditions under which this becomes automatic.

Although considerable work has been done in the LTM domain, impacts of enactment in particular and motoric processing more generally remain a relatively underexplored topic in working memory. How might models of working memory capture the outcomes of the current study? Baddeley, Allen, and Hitch (2011; Baddeley, 2012) suggested a multicomponent model in which a range of information including tactile-kinaesthetic input might enter working memory, with processing and initial storage attributed to the visuospatial sketchpad. This latter component has been further subdivided, with Logie (1995) distinguishing a passive store for visual information (the visual cache) from a system for representing space and movement (the inner scribe). In

line with a relationship between movement and space, concurrent motor movement has been shown to disrupt performance on tasks requiring either memory or mental imagery for spatial paths (e.g. Baddeley & Lieberman, 1980; Quinn, 1994; Quinn & Ralston, 1986; Smyth & Pendleton, 1989). Similarly, Bo and Seidler (2009) have argued that learning of new motor sequences may critically rely on spatial working memory. Thus, movement representation created by either enacting or planning to enact during encoding may be temporarily stored and rehearsed within the inner scribe spatial component of working memory (Logie et al., 2001). This would be consistent with our findings, with maintenance within the inner scribe supplementing other forms of storage (e.g. within the phonological loop), particularly when their capacities are exceeded (i.e. towards the end of each sequence). Thus, it is possible that the current findings may be accommodated within existing multicomponent models of working memory (e.g. Baddeley, 2012; Logie, 1995). However, it is worth noting that when performed concurrently with sequence presentation in FI tasks, spatial tapping (an activity assumed to particularly disrupt the inner scribe component of working memory) does not appear to interact with the enacted recall advantage (Yang et al., 2014). This in turn would indicate that spatial working memory may not be solely responsible for this effect, and that a separable motoric representation (e.g. Smyth & Pendleton, 1989; Sternberg, Monsell, Knoll, & Wright, 1978) might also contribute to enactment effects at both encoding and retrieval.

This interpretation of enactment effects in working memory as reflecting spatial-motoric processing is at least partly drawn from work on LTM (e.g. Engelkamp et al., 2000), and it is possible that other forms of coding may also play an important role. As with any working memory task, participants might draw on a range of information to

support performance, including visual, spatial, verbal, and semantic, as well as motoric and kinaesthetic (Baddeley & Logie, 1999; Logie et al., 2001). In the case of visuospatial information, stimuli were constantly present in all conditions in the present experiment, ensuring equivalent opportunity to utilize these forms of coding. However, the requirement to enact at encoding or recall may have encouraged participants to engage with this information and thus facilitated performance. More broadly, enactment may affect semantic processing (Zimmer, 2001) or help participants to maintain task focus. Therefore, representations specific to motoric and movement processing may not be the only causal factor underlying enactment effects. Regardless of the precise nature of the specific contributory representations involved, the enactment effects observed in the present study clearly indicate how multiple forms of processing can be utilized in order to support task performance. While multicomponent approaches to working memory may capture how these separate processing streams could independently operate, effectively combining initially disparate forms of information into a holistic representation might require a modality-general capacity such as the episodic buffer (Baddeley, 2000; Baddeley et al., 2011). Explicit exploration of this possible component has focused on binding of visual and auditory information (see Baddeley et al., 2011 for a review) and has indicated that this may develop relatively automatically; it may be that the integration of information (possibly including verbal, visual, spatial, and motoric, depending on the condition) in the FI task presently under exploration also proceeds in this way. Thus, different forms of coding, including those emphasized by actual or intended enactment, would be incorporated into a bound representation at little or no additional cost to executive control processes (Yang et al., 2014).

The present findings can be differentiated from previous work concerning benefits of multi-modal encoding on working memory (e.g. Delogu, Raffone, & Belardinelli, 2009), which suggest that multiple input streams can benefit verbal recall, provided these are non-redundant. In the present study, enactment at encoding was always additional to the verbal presentation of instructions, irrespective of response format. Thus, an account based on simple multi-modal presentation would predict similar effects of encoding-enactment across verbal and action recall. Instead, our findings suggest that it is the participants' own anticipation and planning for future action that renders enactment during encoding relatively redundant.

Subsequent research will be required to more clearly ascertain the source of the various enactment effects observed in the current study, and the extent to which they emerge through effortful or automatic processing. However, in line with claims from the LTM literature (e.g. Engelkamp & Zimmer, 1989; Freeman & Ellis, 2003) we would suggest such effects to have an important motoric component. It would be fruitful for future work to consider how such processing may be incorporated into working memory, across different tasks and groups, and how performance in these tasks may correlate with other measures of working memory and wider cognitive function.

References

Bäckman, L., & Nilsson, L. G. (1984). Aging effects in free recall: An exception to the rule. *Human Learning: Journal of Practical Research & Applications*, *3(1),* 51-69.

Baddeley, A.D. (1986). Working memory. Clarendon Press, Oxford.

Baddeley, A.D. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience, 4*, 829-839.

Baddeley, A.D. (2012). Working memory: Theories, Models, and Controversies. *Annual Review of Psychology, 63,* 1-29.

Baddeley, A.D., Allen, R.J., & Hitch, G.J. (2011). Binding in visual working memory: The role of the episodic buffer. *Neuropsychologia, 49,* 1393-1400.

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2009). Working memory and binding in sentence recall. *Journal of Memory and Language*, *61*(3), 438-456.

Baddeley, A. D. & Lieberman, K. (1980). Spatial working memory. In R.S. Nickerson (Ed.), *Attention and performance VIII*, pp. 521-539, Hillsdale, NJ: LEA.

Baddeley, A.D., & Logie, R.H. (1999). Working memory: The multiple component model. In A. Miyake and P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control.* pp 28-61. Cambridge: Cambridge University Press.

Bo, J., & Seidler, R.D. (2009). Visuospatial working memory capacity predicts the organization of acquired explicit motor sequences. *Journal of Neurophysiology, 191,* 3116-3125.

Charlesworth, L.A., Allen, R.J., Morson, S., Burn, W.K., & Souchay, C. (2014). Working Memory and the Enactment Effect in Early Alzheimer's Disease. ISRN Neurology, vol. 2014, Article ID 694761. doi:10.1155/2014/694761

Cohen, R. L. (1981). On the generality of some memory laws. *Scandinavian Journal of Psychology, 22,* 267–282.

Cohen, R. L. (1989). Memory for action events: The power of enactment. *Educational Psychology Review*, *1(1),* 57-80.

Delogu, F., Raffone, A., & Belardinelli, M. O. (2009). Semantic encoding in working memory: Is there a (multi) modality effect? *Memory*, *17*(6), 655-663.

Engelkamp, J. (1998). *Memory for actions.* Hove, UK: Psychology Press.

Engelkamp, J., & Zimmer, H. D. (1989). Memory for action events: A new field of research. *Psychological Research, 51,* 153157.

Engelkamp, J., & Zimmer, H. D. (1995). Similarity of movement in recognition of self-performed tasks and of verbal tasks. *British Journal of Psychology*, *86(2),* 241-252.

Freeman, J. E., & Ellis, J. A. (2003). The representation of delayed intentions: A prospective subject-performed task? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29 (5),* 976-992.

Frith, C. D., Blakemore, S. J., & Wolpert, D. M. (2000). Abnormalities in the awareness and control of action. *Philosophical Transactions Royal Society of London, Series B: Biological Sciences*, *355*, 1771-1788.

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.

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),* 568578.

Logie, R.H. (1995). *Visuo-Spatial Working Memory*. Hove, UK: Lawrence Erlbaum Associates.

Logie, R.H., Engelkamp, J., Dehn, D., & Rudkin, S. (2001). Actions, mental actions, and

    working memory. In M. Denis, R.H. Logie, C. Cornoldi, J. Engelkamp, & M. De Vega

    (Eds.). *Imagery, Language and Visuospatial Thinking,* pp. 161-184. Hove, UK:

    Psychology Press.

Quinn, J.G. (1994). Towards a clarification of spatial processing. *The Quarterly Journal of*

    *Experimental Psychology, 47A, 465-480.*

Quinn, J.G., and Ralston, G.E., (1986), Movement and attention in visual working

    memory. *The Quarterly Journal of Experimental Psychology, 38A, 689-703.*

Saltz, E., & Donnenwerth-Nolan, S. (1981). Does motoric imagery facilitate memory for

    sentences? A selective interference test. *Journal of Verbal Learning and Verbal*

    *Behavior, 20(3),* 322-332.

Smyth, M. M., Pearson, N. A., & Pendleton, L. R. (1988). Movement and working memory:

    Patterns and positions in space. *The Quarterly Journal of Experimental Psychology,*

    *40*(3), 497-514.

Smyth, M.M., & Pendleton, L.R. (1989). Working memory for movements. *The Quarterly*

    *Journal of Experimental Psychology, 41A*, 235-250.

Sternberg, S., Monsell, S., Knoll, R. L., & Wright, C. E. (1978). The latency and duration of

    rapid movement sequences: Comparisons of speech and typewriting. *Information*

    *processing in motor control and learning*, 117-152.

Wojcik, D. Z., Allen, R. J., Brown, C., & Souchay, C. (2011). Memory for actions in autism

    spectrum disorder. Memory, 19, 549–558.

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.

    *Psychonomic Bulletin & Review*, *21,* 186-192.

Zimmer, H. D. (2001). Why do actions speak louder than words: Action memory as a

    variant of encoding manipulations or the result of a specific memory system? In

    H. D. Zimmer, R. Cohen, M. J. Guynn, J. Engelkamp, R. Kormi-Nouri & M. A. Foley

    (Eds.), Memory for action: A distinct form of episodic memory? (pp. 151-198).

    New York: Oxford University Press.

Zimmer, H. D., Helstrup, T., & Engelkamp, J. (2000). Pop-out into memory: A retrieval

    mechanism that is enhanced with the recall of subject-performed tasks. *Journal of*

    *Experimental Psychology: Learning, Memory, and Cognition*, *26*(3), 658.

Footnote

1. Mean proportion of pairs correctly recalled in any serial position (i.e. item memory,

regardless of order) was also analyzed, and produced the same outcomes as the serial

recall measure.

Figure captions

Figure 1. Mean proportion of action-object pairs correctly recalled in each encoding and recall condition. Error bars denote standard error.

Figure 2. Mean proportion of action-object pairs correctly recalled as a function of serial position in each encoding condition, through a) verbal recall and b) enacted recall. Error bars denote standard error.
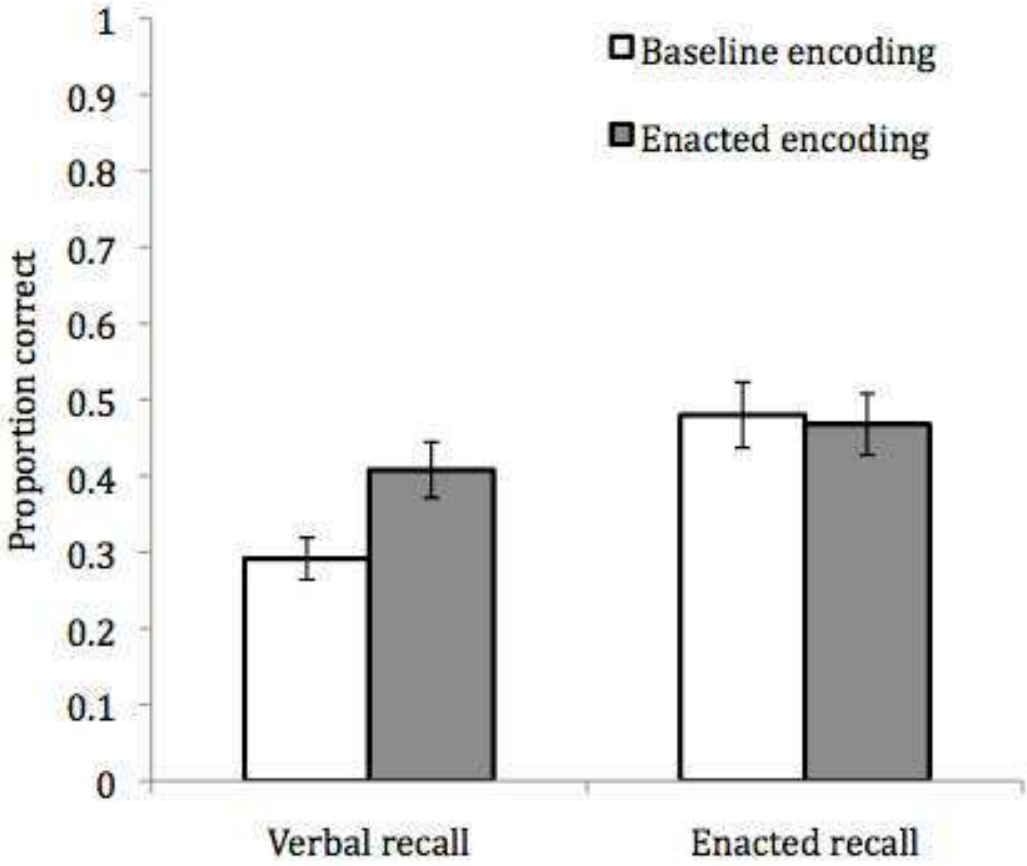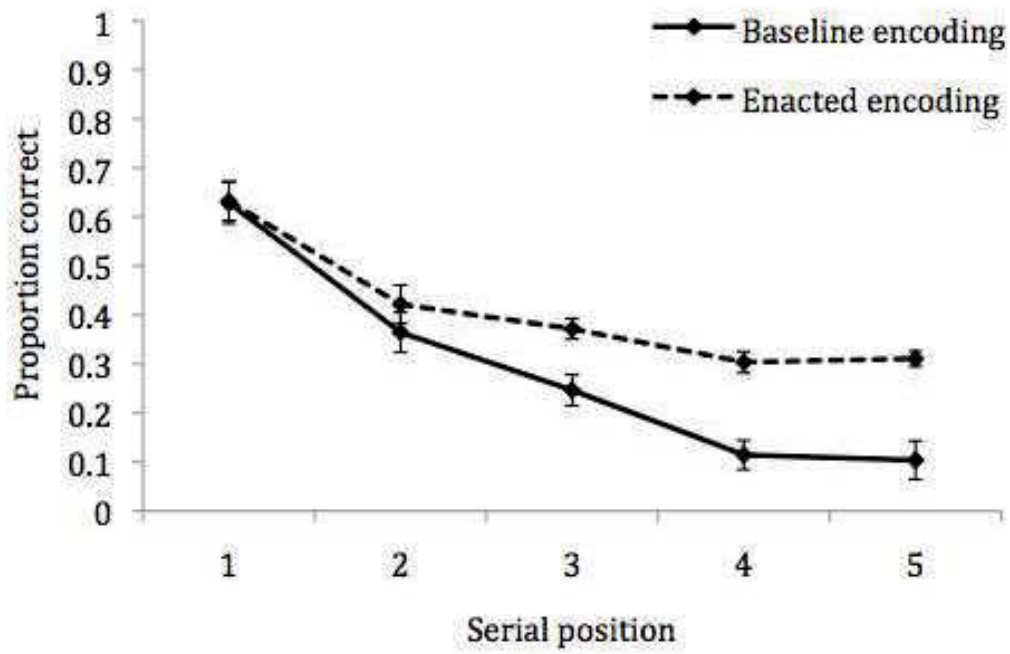
Figure 1

Figure 2



a). Verbal recall

b). Enacted recall