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Memory enhancements from active control of learning in children with autism spectrum disorder

Valentina Fantasia[1], Douglas B. Markant[2], Giovanni Valeri[3], Nicholas Perri[4,5] and Azzurra Ruggeri[5]

Abstract

Previous research with typically developing children and adults shows that active control of the learning experience leads to enhanced episodic memory, as compared with conditions lacking this control. The present study investigates whether similar advantages can be found in children with autism spectrum disorder. In this study, 6–12-year-old autistic children ($N = 29$) participated in a simple memory game on a touchscreen tablet, in which they were asked to remember 64 objects presented in four blocks of 16. In two of the blocks, children could decide the order and pacing of study (active condition), whereas in the other two blocks, they passively observed the active study decisions of a previous participant (yoked condition). We found that recognition memory was more accurate for objects studied in the active compared with the yoked condition, even after a week-long delay. The magnitude of the effect was comparable with that obtained in previous studies with typically developing children and adults, suggesting a robustness for the benefits of active learning that goes beyond what previously hypothesized, extending to special populations. We discuss how these findings may help develop pedagogical interventions that leverage the active learning approach to promote inclusive learning.

Lay abstract

Research with adults and typically developing children has shown that being able to *actively control* their learning experience, that is, to decide what to learn, when, and at what pace, can boost learning in a variety of contexts. In particular, previous research has shown a robust advantage of active control for episodic memory as compared with conditions lacking this control. In this article, we explore the potential of active control to improve learning of 6- to 12-year-old children diagnosed with autism spectrum disorder. We presented them with a simple memory game on a touchscreen tablet, in which children were asked to recall as many of the presented objects as possible. For half of the objects, children could decide the order and pacing of study (active condition); for the other half, they passively observed the study decisions of a previous participant (yoked condition). We found that recognition memory was more accurate when children could actively control the order, pace, and frequency of the study experience, even after a week-long delay. We discuss how teachers and educators might promote active learning approaches in educational and pedagogical applications to support inclusive learning.

Keywords

active learning, autism spectrum disorder, enactment effect, exploration, recognition memory

Introduction

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by persistent social and communication difficulties, as well as restricted interests, repetitive activities, and sensory abnormalities (American Psychiatric Association, 2013). Crucially, ASD also affects the way individuals attend to, select, and process information. For example, children with autism tend to fixate on particular, single details therefore losing touch with a more general, comprehensive picture, and often fail

[1]Department of Social and Developmental Psychology, Sapienza, University of Rome, Italy
[2]University of North Carolina at Charlotte, USA
[3]I.R.C.C.S Ospedale Pediatrico Bambino Gesù, Italy
[4]Mind and Brain, Humboldt-Universität zu Berlin, Germany
[5]MPRG iSearch, Max Planck Institute for Human Development, Germany

Corresponding author:
Valentina Fantasia, Research Fellow, Department of Social and Developmental Psychology, Sapienza, University of Rome, Via dei Marsi 78, 00185 Rome, Italy.
Email: valentina.fantasia86@gmail.com

to attend or disregard socially salient stimuli (Green et al., 2016; Klin, 2000; Nummenmaa & Calder, 2009). These difficulties are potentially impairing their possibilities for learning (Björne, 2007; Greenspan, 2006), and may be associated with weaknesses in the memory domain, which have often been reported among high-functioning individuals with ASD (Boucher et al., 2012).

Recent research with neurotypical children and adults has shown that giving learners some control over the learning experience (e.g., to decide the order and pacing of study) results in memory benefits that last over a week-long delay (Harman et al., 1999; Liu et al., 2007; Markant et al., 2014; Meijer & Van der Lubbe, 2011; Plancher et al., 2013; Ruggeri et al., 2019; Voss, Galvan, & Gonsalves, 2011; Voss, Gonsalves, et al., 2011; Voss, Warren, et al., 2011). Following on evidence of improved recognition memory from active control among typically developing (TD) children (Ruggeri et al., 2019), in this article, we explored whether active control of study would lead to similar benefits for children diagnosed with high-functioning ASD. Our results have the potential to orient future educational research and practice, supporting the development of tailored, more inclusive educational programs, and interventions that promote active learning for children with ASD.

Memory and learning in ASD

Children with autism, even in the absence of severe intellectual disability, face a variety of learning challenges, including poor reading comprehension (Davidson & Ellis Weismer, 2014; Davidson et al., 2018), word reading deficits (Lindgren et al., 2009; Lucas & Norbury, 2014), and difficulties using language in a flexible and creative way and thinking abstractly (Rao & Gagie, 2006). Moreover, children with ASD tend to explore space and objects less than TD children (Björne, 2007), engaging in restricted interactions with unfamiliar objects, and often focusing on only a limited range of features. These difficulties put ASD children at risk of missing crucial opportunities for learning, those that lie beyond their (often narrow) interests (Pellicano & Burr, 2012; Plaisted et al., 1998).

The specific memory profile associated with ASD (for extensive reviews, see Boucher et al., 2012; Bowler et al., 2011; Desaunay et al., 2019) may contribute or even drive some of these learning difficulties, as memory anomalies impact "how and what an individual learns, which will in turn affect (. . .) the ways in which an individual experiences and responds to the external world" (Boucher et al., 2012, p. 461). Research to date converge in reporting difficulties in declarative memory tasks that require the encoding and retrieval of contextually rich information, as opposed to tasks assessing memory for single items (e.g., objects, words, sounds). For example, studies have shown that recognition of non-social stimuli is relatively preserved in individuals with high-functioning autism, but impaired when the presented stimuli consist of specific feature associations, complex scenes (Bowler et al., 2010; D. L. Williams et al., 2006b), or semantically related items (e.g., lists of related words or pictures), or include social or affective content (e.g., difficulties with processing and remembering faces, Webb et al., 2010). Although cued recall is typically less challenging for TD individuals—as when category labels ("Which *fruit* did you see?") facilitate the recall of lists of words or pictures (Boucher & Warrington, 1976; Bowler et al., 2009), or being offered one item helps remembering the one it was paired with ("Which word went with 'Card'?"), individuals with high-functioning autism do not necessarily benefit from being cued (Ambery et al., 2006; Bigham et al., 2010; Brown et al., 2005; Minshew & Goldstein, 2001). Results from previous studies on declarative memory for visuospatial tasks in high-functioning adults with autism present similar patterns. For example, spatial memory capacity seems to be intact when the stimuli consist of novel locations and colors of novel objects assessed separately, but is impaired when stimuli are presented as rich combinations of information (e.g., object-location or object color combinations; Bowler et al., 2010).

The picture is even less clear when considering studies with children on the spectrum, where memory performance seems to be more strongly influenced by the task nature (Botting, Conti-Ramsden, 2003; Verté et al., 2006; D. L. Williams et al., 2006b). For example, visuospatial abilities appear unimpaired in high-functioning children with autism when assessed through spatial span forward tasks (e.g., using the Corsi block test; D. L. Williams et al., 2006a; Zinke et al., 2010). Similarly contradicting, free recall of spatial locations assessed through visuospatial search tasks, where spatial locations of geometrical shapes appearing on a screen had to be recall, is reported as intact in adolescents by Ozonoff and Strayer (2001), but as impaired by Steele et al. (2007).

Researchers have offered different accounts of these discrepancies in declarative memory observed in high-functioning individuals with ASD, which diverge in the cognitive functions and domains that are assumed to be involved. Recently, researchers have proposed that the variety and complexity of memory profiles in ASD may be attributed to the interplay of recollection and familiarity processes (Bigham et al., 2010; Boucher & Mayes, 2012; Joseph et al., 2005), two separable memory retrieval processes contributing to recognition memory. Recollection refers to the retrieval of qualitative, contextual information about a specific episode (e.g., when or where an event took place), whereas familiarity refers to a more general measure of memory strength or stimulus recency that does not necessarily bring along any other information. Usually assessed through the remember–know paradigm (Gardiner & Java, 1993), these processes have been empirically tested by

Bigham et al. (2010), who implemented a novel double-task paradigm to assess recollection and familiarity separately. The recollection task involved manual actions that were arbitrarily associated with meaningless shapes that had to be recalled, whereas familiarity was assessed through a spatial source memory task in which similar non-meaningful stimuli had to be recognized. According to the authors, in this latter case, participants relied mostly on a "feeling that one of the four items has been seen before" (p. 883). The study confirmed recollection and familiarity as distinct and individually measurable components, as results showed mild impairments in recalling of manual actions, but no anomalies in familiarity processes.

Improved memory from active control during study

Self-directed, active learning is often associated with better short- and long-term memory retention. Previous research with adults has investigated the benefits of active learning using simple memory games, in which participants were tasked to study and remember a set of objects arranged on a grid, with only one object visible at a time (Markant et al., 2014; Voss, Galvan, & Gonsalves, 2011; Voss, Gonsalves, et al., 2011). Crucially, most of these studies adopted a "yoked" design, where participants alternate between *active* study blocks, in which they can control the study sequence and timing by deciding which objects to view, and *yoked* study blocks, in which they observe the study sequence that a previous participant had generated in an active study block. By matching the content experienced during study across conditions, yoked designs isolate the effects of active control on learning and memory. These studies have found that participants were more accurate at recognizing objects that had been actively studied as compared with those studied in the yoked condition (see Harman et al., 1999; Liu et al., 2007; Markant et al., 2014; Meijer & Van der Lubbe, 2011; Plancher et al., 2013; Voss, Galvan, & Gonsalves, 2011; Voss, Gonsalves, et al., 2011; Voss, Warren, et al., 2011). This advantage has been shown to emerge during early childhood, becoming comparable in magnitude with adults by age 8 (Ruggeri et al., 2019), to persist a week after study (Ruggeri et al., 2019; Voss, Galvan, & Gonsalves, 2011), to be robust across a variety of related tasks and materials (Harman et al., 1999; Liu et al., 2007; Markant et al., 2014; Meijer & Van der Lubbe, 2011; Plancher et al., 2013), and across populations of learners of different nationalities (Ruggeri et al., 2019). Importantly, these studies also revealed that the advantage of active study depended on how participants explored the objects. In particular, allocating greater study effort, either in terms of number of visits or the total time spent studying an object, generally led to more accurate recognition (Markant et al., 2014; Ruggeri et al., 2019; Voss, Galvan, & Gonsalves, 2011).

This advantage from active study resonate with results from studies that used self-performed tasks (SPTs; Cohen, 1981). In these tasks, participants are presented with action phrases (e.g., "Clap your hands") that they either have to read/perform (*self-performed* condition) or that are read/performed by someone else (*other-performed* condition). Results from neurotypical individuals have convergently indicated that participants remembered the actions they had performed themselves better than those they just read aloud by themselves (Engelkamp et al., 1994; Engelkamp & Zimmer, 1994). This memory advantage associated with being an active agent rather than an observer, referred to as the *enactment effect*, has proved to be extremely robust and is thought to result from enriched episodic memories that include motor or proprioceptive information (Engelkamp & Zimmer, 1994; Zalla et al., 2010). Also, results from TD children have shown that the enactment effect emerge around 8 years of age and systematically increase across childhood (Badinlou et al., 2017; Foley & Johnson, 1985). Interestingly, the enactment effect has been also investigated with populations affected by ASD, leading to seemingly inconsistent results. While, some studies have reported reduced or absent enactment effect in individuals with ASD as a result of impaired or diminished action-monitoring systems (Farrant et al., 1999; Millward et al., 2000; Wojcik et al., 2011), other studies reported evidence of intact enactment effects both in adults and in children with ASD (Grainger et al., 2013; Wojcik et al., 2011; Yamamoto & Masumoto, 2018). Mixed results also emerged within studies testing SPT in autism by means of different memory domains (Zalla et al., 2010), reflecting the overall heterogeneity of memory profiles within the autism spectrum.

SPT paradigms present important methodological limitations that may reduce their ecological validity in the case of autism. For instance, in SPTs, the content of the tasks differs between the self-performed and others-performed conditions. Instructions given for participants to perform an action are grammatically different from those presented as instructions given to the experimenter (as others-performed condition), creating a potential bias toward SPTs, which may be perceived, for instance, as more familiar. To overcome this limitation, Williams and Happé (2009) designed a task in which children with autism were asked to self-perform an action and to perform the same action on behalf of a doll that represented a separate agent. The authors found that memory was better for actions that had been self-performed, suggesting that even the enactment effect cannot be exclusively attributed to motor engagement. Additionally, a recent meta-analysis highlights that only 2% of the ASD studies published in 2016 (301 in total) included non- or minimally verbal participants (Russell et al., 2019). This bias is especially concerning because the estimation of ASD children who are non- or minimally verbal by the time they enter kindergarten is around 25%–35%

(Rose et al., 2016), suggesting that SPTs, and more generally verbal tasks, might not be the most methodologically appropriate.

The present study overcomes some of these limitations by implementing a non-verbal recognition and visuospatial memory task, previously used with adults and TD children (see Ruggeri et al., 2019), to explore whether and how active control of the study experience influences memory for novel objects in children with high-function autism.

The present study

The present study aimed to explore the benefits of active learning in high-functioning children with ASD by examining their recognition memory for objects studied in an active compared with a yoked learning condition. We adopted a task developed for TD children by Ruggeri et al. (2019), which taps onto two different components of declarative memory: recognition memory for single, decontextualized items, and recall of their original spatial location. Compared with SPT paradigms used in previous studies with autism population, our design presents several advantages. First, it is a completely non-verbal paradigm, overcoming the methodological limitation presented in SPTs and making it suitable for participants with atypical development and difficulties in communication. Second, because difficulties in understanding and imitating others' actions are frequently observed in children within the spectrum (Chetcuti et al., 2019), we adopted stimuli that are not associated with performing an intended or goal-directed action, contrarily to what standard SPTs usually do (Vivanti & Rogers, 2011). Third, participants were instructed to perform the same motor actions (e.g., touching the objects to be studied) in both conditions. In this way, we could disentangle the effects of active control from those of motor engagement which are confounded in SPT paradigms. In addition, due to its yoked design, our paradigm matches the content experienced during study across conditions, so that the effects of active control of study on learning and memory could be isolated. Finally, participants were assessed using a tablet device with an interactive interface, particularly suitable for testing children with autism. Indeed, interactive teaching strategies (i.e., visual-interactive materials paired with music) seem to enhance active engagement and learning of autistic students (Carnahan et al., 2008). Moreover, past research has shown that ASD children are more attentive and motivated in tasks involving technological tools, resulting in better performance, and enjoyment of intervention sessions (Moore & Calvert, 2000).

Based on previous studies demonstrating diminished memory for contextual details but intact item recognition in autistic individuals (see Boucher et al., 2012, for a review), we expected the high-functioning children in our study to show active learning benefits to memory comparable with those found in TD children of the same age (Ruggeri et al., 2019). Given the mixed results emerging from research on visuospatial memory of children with ASD, reviewed in the introduction, we did not have a clear hypothesis as to whether active control would improve spatial memory. Moreover, even results from active learning research with neurotypical individuals present variable evidence on this effect (Markant et al., 2014; Ruggeri et al., 2019; Voss, Galvan, & Gonsalves, 2011; Voss, Gonsalves, et al., 2011; Voss, Warren, et al., 2011).

Method

Participants

Twenty-nine 6- to 12-year-old children (4 females, $Mage = 114.52$ months; $SD = 21.15$ months) were recruited from the Neuropsychiatry and Neuroscience Unit, I.R.C.C.S. Bambino Gesù Pediatric Hospital (OPBG), Rome, Italy. Data from six additional children were excluded due to testing and technical difficulties.

All participants were native Italian, with medium to high socioeconomic status, and were recruited through the hospital database. All of them had received a formal diagnosis of autism and had been administered the Autism Diagnostic Observation Schedule—Second Edition (ADOS-2; Lord et al., 2013). To reduce heterogeneity within our sample, and to ensure that typical autism-related symptoms, such as stereotyped or repetitive motor behaviors did not interfere with the manual performance required by the experimental task, we recruited only children who had scored between 5 and 8 out of 10 on the previously administered ADOS-2 ($M = 6.17$; $SD = 1.04$). During the experimental session, we additionally assessed participants' IQ ($M = 109$; $SD = 13.55$) using the Raven's Colored Progressive Matrices (RCPM, Raven et al., 1990), as well as their verbal abilities, assessed with the Peabody Picture Vocabulary Test–Revised (PPVT-R; Dunn & Dunn, 1981; Italian version by Stella et al., 2000) and the Vineland Adaptive Behavior Scales-II (VABS-II; Sparrow et al., 2005 Italian version by Balboni et al., 2016). PPVT and VABS mean scores are reported in Table 1, along with children's demographic information.

Written informed consent was obtained from participants' caregivers and the ethical review board of the Max Plank Institute for Human Development, Berlin.

Materials

As in the work of Ruggeri et al. (2019), the stimuli consisted of 200 lines drawings of the most frequent objects mentioned by 2- to 5-year-old children in their everyday conversations with adults, as recorded by the CHILDES corpus (Child Language Data Exchange System; MacWhinney & Snow, 1985). To minimize perceptual differences, all objects included in the set were drawn using

Table 1. Descriptive characteristics of study sample.

	Mean	*SD*	Range
Chronological age (months)	114.52	21.15	73–151
ADOS-2[a]	6.17	1.04	5–8/10
RCPM	109	13.55	88–130
PPVT-R	81	19.28	73–104
VABS-II communication domain[b]	75.35	12.43	68–89

ADOS: Autism Diagnostic Observation Schedule; RCPM: Raven's Colored Progressive Matrices; PPVT-R: Peabody Picture Vocabulary Test-Revised; VABS-II: Vineland Adaptive Behavior Scales-II.
[a]ADOS comparison score (scale range: 1–10). [b]Standardized score ranges for this test are as follows: 70–80 borderline adaptive functioning; 51–55–70: mildly deficient adaptive functioning.

the same stroke, color palette and coloring style. Eight of the 200 drawings were used as training stimuli for the familiarization trials and 192 drawings were used as stimuli for the experimental sessions. The experimental materials were presented on an Android touchscreen tablet using custom software.

Design and procedure

The experimental procedure was identical to that implemented in Study 2 by Ruggeri et al. (2019). The stimuli were presented in a simple memory game, where children were tasked to remember as many of the presented objects as possible.

Familiarization phase. Participants were first presented with two familiarization trials aimed at introducing the instructions and goal of the game, making children comfortable using the touchscreen. During each familiarization trial, children were presented with four objects arranged in a 2 × 2 grid. The objects were shown on the screen for 2 s before disappearing under occluders (same as for the main experimental session, see Figure 1, top). Participants were instructed that the goal of the game was to remember all the objects presented on the screen. The first familiarization trial introduced the study procedure of the active blocks. Participants were told that in some rounds they could decide which occluder button to touch to view and study the object hidden beneath. After touching the occlude button, a red frame appeared for 500 ms, followed by the removal of the occluder that revealed the hidden object. Children were instructed that, before studying another object, they had to touch the object currently displayed once more to make it disappear behind the occluder. The experimenter modeled the touching actions while explaining the procedure. Children then had the opportunity to practice the active study procedure. If necessary, the experimenter provided feedback and repeated the instructions. Once children were familiar with the active study procedure, they were presented with the second familiarization trial, which introduced children to the study procedure of the yoked blocks. Children were told that in other rounds, the game would decide what objects they would see and for how long, and then presented with a randomly generated study sequence. As in the active blocks, a red frame preceded each object for 500 ms, so that children had time to allocate their attention to the new study location before the object appeared. To keep engagement and attention level comparable with the active blocks, during yoked blocks, children were asked to touch the objects as soon as they appeared, although this touch had no effect on the display. There were no time constraints for the familiarization trials.

Study phase. The main experimental session consisted of two active and two yoked study blocks (four blocks total), presented in alternating order (i.e., active, yoked, active, yoked). Across the four blocks, children were asked to memorize 64 objects. The active block was always presented first, so that children's initial active study pattern would not be influenced by the study pattern observed in the yoked blocks. Each study block presented children with 16 objects arranged in a 4 × 4 grid. Objects were visible on the screen for 2 s at the beginning of each study block, before disappearing under occluders (see Figure 1, top). In the active blocks, children had 90 s to select and study the objects to memorize them. In the yoked blocks, children were presented with the 90-s study sequence (i.e., same objects and pacing) of one of the previous participants' active learning blocks. There was a 20-s break in between blocks, in which children were briefly reminded of the study procedure for the next block.

Test phase. The study phase was immediately followed by a test phase consisting of eight blocks. In each test block, as for the study blocks, 16 objects were presented arranged in a 4 × 4 grid (Figure 1, bottom). Across the eight test blocks, 64 of the objects had appeared during the study phase (*old* objects) and 64 were *new* objects that were not presented during study. The number of old objects in each block was randomly varied between 1 and 15, with each test block including items from both active and yoked studies (active: $M=4.01$, $SD=2.36$; yoked: $M=3.97$, $SD=2.34$). All objects were arranged in random locations on the grid.

For each block, children were asked to select the objects they had previously seen, by touching them on the screen; once selected, objects were framed in red. Children could deselect any of the previously selected objects by touching them again on the screen and making the red frame disappear. After selecting those objects they recognized, children were asked whether each object was currently in the same position on the grid as where it had appeared during the study phase (spatial recognition test, see Figure 1, bottom right). Children were then

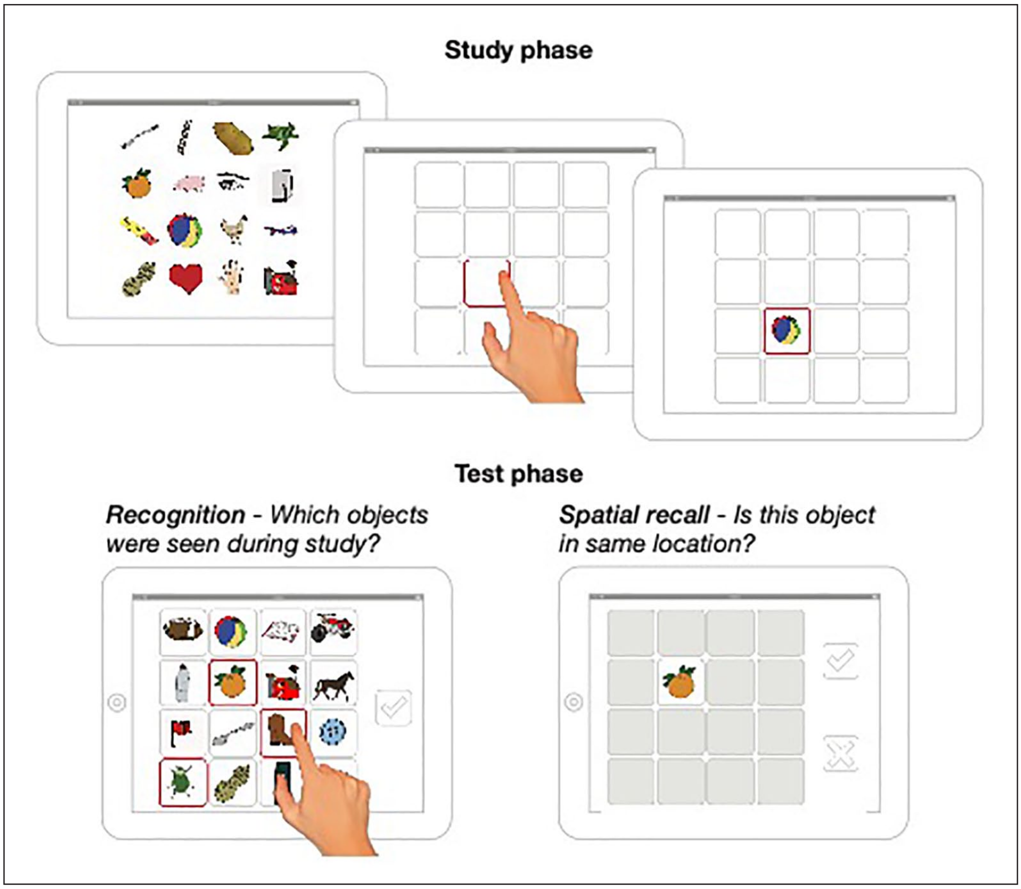

Figure 1. Top: Each study round began with all objects displayed for 2 s. After the objects disappeared, participants either selected a location to study (active condition), causing a red frame to appear, followed by the object, or touched the location where the object appeared (yoked condition), preceded by a red frame. **Bottom left:** During each test block, participants selected the objects that they recognized from the study phase. **Bottom right**: Spatial recognition test. For objects that were recognized, participants judged whether they were presented on the test grid in the same location as where they had appeared during study.

prompted to touch a button to proceed to the next test block and were not given any feedback about their performance during or after the test phase.

About 1 week later (range 5–8 days; $M = 7.2$ days; $SD = 0.72$ days), children revisited the hospital for a second session, in which they were asked to complete eight new test blocks. The 64 objects studied in the first session were randomly mixed with 64 completely new objects.

Results

Recognition of studied objects

Model selection. Mixed effects logistic regression was used to model recognition responses ("old" vs "new") for objects presented during the study phase. All mixed effects models were fit using the *lme4* library in R (Bates et al., 2014). First, a baseline model was defined that included the following fixed effects: age in months (continuous); study condition (active vs yoked); testing session (test vs retest); location of the item at test (same vs different locations from study); and false alarm rate (continuous), to control for participants' tendency to respond "old." Two additional predictors were included to assess item-level effects of study behavior: cumulative study duration (i.e., the total amount of time a certain object was studied) and number of visits (i.e., the number of times the object was visited). Non-categorical predictors were scaled and centered prior to model fitting. Study duration was square-root-transformed to correct for positive skew. Random intercepts were estimated for both participants and items (Baayen et al., 2008). In addition, a random effect of condition was estimated for participants (including additional random effects led to convergence failures). In addition to the fixed effects above, we included terms for the interaction between study condition, testing session, and item-specific attributes (study duration, number of visits, and whether the item changed positions from study to test). We generated 189 potential models representing all possible combinations of interactions of interest. The best-fitting model was selected based on the minimum Akaike information criterion (AIC). In addition to the baseline fixed

Table 2. Estimated effects from logistic regression model of recognition accuracy.

Predictor	*OR*	95% *CI*	*Wald z*	*p*
(Intercept)	1.88	1.25–2.84	3.13	0.002
Age	0.93	0.66–1.30	–0.44	0.662
False alarm rate	1.16	0.99–1.36	1.88	0.060
Condition (yoked)	0.59	0.44–0.78	–3.75	<0.001
Test (retest)	0.54	0.43–0.69	–5.00	<0.001
Half (second)	1.19	1.01–1.40	2.09	0.036
Location (different)	1.05	0.90–1.24	0.64	0.523
Number of visits	1.23	1.08–1.24	3.00	0.003
Study duration	1.82	1.57–2.12	7.89	<0.001
Test (retest) × condition (yoked)	1.31	0.94–1.82	1.62	0.106
Test (retest) × study duration	0.87	0.73–1.04	–1.55	0.120

OR: odds ratio; CI: confidence interval.

effects, the best-fitting model included the interaction between test session and cumulative study duration.

Model results. Table 2 presents the parameters of the best-fitting model. Effect sizes and 95% confidence intervals are reported in terms of relative odds ratio (OR), which indicates the multiplicative change in the odds of recognizing a studied item that is associated with a unit change in a given predictor. Results from the logistic regression showed that recognition accuracy was higher for objects studied in the active condition in both the test (active: $M=0.63$, $SD=0.20$; yoked: $M=0.53$, $SD=0.20$) and the retest (active: $M=0.54$, $SD=0.22$; yoked: $M=0.48$, $SD=0.20$; Figure 2). Accuracy was lower for items studied in the first half of the study phase (i.e., within the first two blocks of presented objects; $M=0.53$, $SD=0.17$) compared with the second half ($M=0.57$, $SD=0.19$). Objects were more likely to be recognized when visited more often and studied for longer times for both test and retest, although the positive effect of study duration was weaker in the retest ($OR=1.58$ [1.35, 1.85]). The model revealed no interaction between condition and study duration, indicating that the effects of additional study at the item level (either in terms of number of visits or total study duration) were consistent across study conditions. Finally, there were no effects of age ($OR=0.93$ [0.66, 1.30]), false alarm rate ($OR=1.16$ [0.99, 1.36]), or the item appearing in the same/different locations at test ($OR=1.05$ [0.90, 1.24]).

Spatial memory accuracy

We implemented the same model selection procedure as for the item recognition analysis (see section above), with the exception that the false alarm rate was not included as a fixed effect. In addition to the remaining fixed effects in

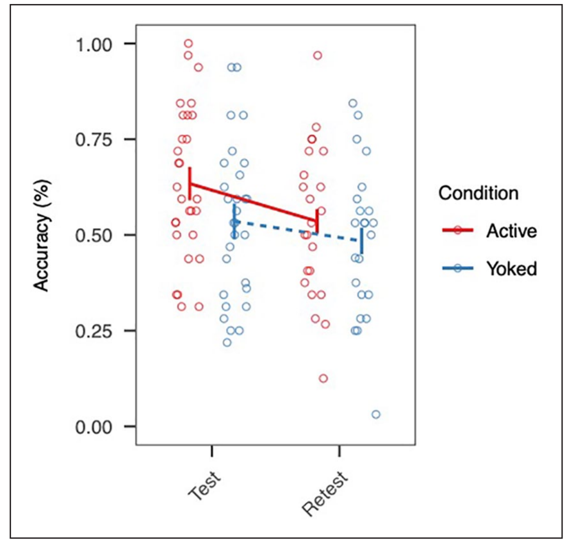

Figure 2. Recognition accuracy for objects in active (red) and yoked (blue). Individual points represent participants. Error bars represent within-subjects 95% confidence intervals calculated using the Cousineau–Morey method (Morey, 2008).

the baseline model, the best-fitting model included the interaction between test session and item location at test.

Table 3 presents the parameters of the best-fitting model. The results indicated that spatial accuracy was higher for objects appearing in the same location ($M=0.82$, $SD=0.18$) than for objects appearing in a different location ($M=0.45$, $SD=0.31$) in the first test session. In addition, there was a significant decrease in spatial accuracy for objects appearing in a different location in the retest ($M=0.32$, $SD=0.30$). In contrast, accuracy in the retest for items appearing in the same location did not differ from the initial test ($M=0.72$, $SD=0.26$). Within test sessions, spatial accuracy was higher for items studied in the second half of the study phase ($OR=1.31$ [1.06, 1.62]), and for items that were studied for longer total durations ($OR=1.16$ [1.00, 1.33]). There was no effect of the number of visits, age, or study condition on spatial accuracy.

Study behavior in the active study blocks

Participants studied an average of 29.6 ($SD=4.34$) of the 32 objects presented (93%) during the active study blocks. In addition to the item-level study behavior analysis presented above, we examined how participants explored the grid during active blocks and how their search behavior was related to overall performance in the recognition test (see Table 4).

We used the following measures to assess exploration behavior: (1) average study duration, (2) visitation rate, that is, the number of visits per object, averaged across all objects within a block; (3) mean movement distance between successive objects (i.e., how far the participants

Table 3. Estimated effects from logistic regression model of spatial accuracy.

Predictor	*OR*	*95% CI*	*Wald z*	*p*
(Intercept)	4.16	3.25–5.39	11.07	<0.001
Age	1.04	0.90–1.19	0.56	0.574
Condition (yoked)	0.97	0.79–1.20	–0.30	0.768
Test (retest)	0.60	0.49–0.75	–4.60	<0.001
Half (second)	1.31	1.06–1.62	2.52	0.012
Location (different)	0.15	0.12–0.18	–17.47	<0.001
Number of visits	1.00	0.87–1.14	–0.04	0.970
Study duration	1.16	1.00–1.33	1.99	0.046

OR: odds ratio; CI: confidence interval.

Table 4. Measures of study behavior during active study blocks.

	First half *M (SD)*	Second half *M (SD)*
Study duration	1.71 (0.61)	1.75 (0.77)
Visitation rate	1.55 (0.59)	1.52 (0.45)
Movement distance	1.42 (0.25)	1.35 (0.18)
Sequence entropy	1.19 (0.53)	1.34 (0.52)

Table 5. Mixed effects model of recognition performance with aggregate search measures.

Predictor	*OR*	*95% CI*	*Wald z*	*p*
(Intercept)	1.67	1.17–2.41	2.90	0.004
Age	0.98	0.72–1.31	–0.17	0.865
False alarm rate	1.13	0.98–1.30	1.64	0.100
Condition (yoked)	0.70	0.57–0.87	–3.30	0.001
Test (retest)	0.67	0.57–0.78	–4.96	<0.001
Half (second)	1.17	1.01–1.36	2.09	0.037
Visitation rate	1.11	1.00–1.23	2.01	0.044
Sequence entropy	1.00	0.85–1.17	–0.03	0.973
Condition (yoked) × sequence entropy	0.81	0.66–0.99	–1.96	0.050

OR: odds ratio; CI: confidence interval.

moved to select the next object, measured in Euclidean distance); and (4) sequence entropy, a measure of how systematically participants explored the grid. Sequence entropy was calculated as follows: for each block, a 4×4 transition matrix was constructed to represent all possible transitions from the object currently studied (positioned at the top left corner of the matrix) to different locations in the grid, such that all transitions were in the positive x and y directions. We then measured the proportion of transitions that occurred in each observed study sequence and calculated the Shannon (1948) entropy of this distribution. For example, if a participant repeatedly selected the same object to study for an entire block, sequence entropy would be zero; if she followed a consistent search pattern (e.g., always moving left-to-right within each row), sequence entropy would be relatively low; if new locations were chosen at random, sequence entropy would be high (with a maximum value of 2.77 nats, if all transitions were made with equal frequency).

We modeled the effects of these search measures on overall recognition performance (proportion of objects that were correctly recognized) using mixed effects logistic regression. A baseline model was constructed that included fixed effects of age, false alarm rate, condition, test session, and half. We enumerated a set of 81 models based on all possible combinations of the four search measures (mean study duration, visitation rate, movement distance, and search entropy) and their interaction with condition. The model with the lowest AIC was selected as the best-fitting model. Note that the interaction between condition and visitation rate was not included in the best-fitting model, indicating that the effects of number of visits were consistent across study conditions. Random intercept terms were included for participants as well as a random effect of condition

The parameters of the best-fitting model are shown in Table 5. The model shows a significant positive effect of visitation rate, where higher frequency of visits across objects in a block was associated with improved recognition ($OR = 1.11$ [1.00, 1.23]). In addition, there was a significant negative interaction between condition and sequence entropy, indicating that more random search patterns were associated with poorer recognition of items in yoked condition ($OR = 0.81$ [0.70, 0.93]). There was no effect of sequence entropy in the active condition ($OR = 1.00$ [0.85, 1.17]).

Finally, we examined whether within-subjects differences between active and yoked studies were attributable to differences in the systematicity of the study behavior between participants and the partners to whom they were yoked. For instance, a child who implements a highly systematic search strategy (i.e., with low sequence entropy) might have difficulty when observing more random search sequences during yoked study. For each participant, we calculated difference scores between the active and yoked conditions, for overall recognition accuracy in the initial test and for each search measure (visitation rate, movement distance, study duration, and sequence entropy). Within-subjects differences in accuracy were negatively correlated with differences in sequence entropy, $r(27) = –0.38$, $t(27) = –2.1$, $p = 0.04$: Children were penalized and had lower recognition accuracy in the yoked condition when the observed search patterns were more random than those they had generated during active study. This analysis should be interpreted with caution, as a closer look at the distribution highlighted one outlier who is strongly impacting the overall results. There were no other significant correlations (all $p > 0.22$).

Discussion

The present study investigated whether active control over the study experience enhances declarative memory in 6- to 12-year-old high-functioning children with ASD. Our findings indicate that recognition was more accurate in the active compared with the yoked condition, and that improvements from active study condition persisted for a week after the initial study session. In other words, recognition was more accurate when children were able to choose what and how to study. In the Supplementary Online Materials (SOM), we present a signal detection analyses comparing our results with those of the TD children ($N=34$) from Study 2 of Ruggeri et al. (2019), which used an identical procedure. These results indicated that both the discriminability (d') for item recognition and the magnitude of the advantage from active study were lower among ASD children than among the TD group. However, in line with previous research showing that recognition of single, unrelated objects is intact in high-functioning children with autism, the magnitude of the active study advantage for recognition accuracy (test: 10%; retest: 6%) was still similar to that observed in TD children (7.5%–15%; see Ruggeri et al. 2019) as well as in adults (6%–10%; see Markant et al., 2014), and also to that of the enactment effect, as captured by SPTs (10%, see Grainger et al., 2014 for a summary). While these effects may seem modest, improvements in retaining information under active conditions of study might constitute a crucial protective factor, in the long run, for ASD children's educational path.

In addition to item recognition, our task assessed retrieval of visuospatial information by asking participants to judge whether the recognized objects had appeared in the same location as during study. We found similar results to those reported by Ruggeri et al. (2019; see SOM for a direct comparison with our sample), with substantial declines in performance in the delayed retest and no benefit of active control for spatial memory performance, echoing findings from a similar task in adults (Markant et al., 2014). Finally, in line with prior work, we found that our participants' recognition accuracy was influenced by their search behavior, as allocating greater effort to study the stimuli, either in terms of number of visits or total time spent studying an object, lead to more accurate recognition and, to some extent, spatial memory. This result could be explained in terms of general anomalies in visual exploration patterns in autism, with intact or enhanced attention to individual details rather than wide-ranging exploration (Heaton & Freeth, 2016). Visual exploration, particularly toward social stimuli (such as faces, or performed actions), is diminished in children with autism compared with age-matched TD (Elison et al., 2012) and associated with a greater perseverance and are more detail-oriented exploration strategy of visual stimuli.

We found that performance was generally more accurate among participants with higher visitation rates. In general, differences in search behavior alone cannot explain the differences between active and yoked studies, because additional study benefited both conditions, in contrast to the results of Voss, Galvan, and Gonsalves (2011) and Voss, Warren, et al. (2011) and aligned with the results of Markant et al. (2014) and Ruggeri et al. (2019). Interestingly, performance was more accurate for participants implementing more regular search patterns, that is, characterized by lower sequence entropy, but only in the yoked condition. This indicates that more random search patterns impaired recognition memory only in the yoked condition, that is, only when observed but not when self-generated. Our results even suggest that the advantage of active control of study could be explained by a mismatch of expected versus actual study patterns in the yoked condition. That is, participants performed worse in the yoked condition when they received more random study patterns than those they had implemented in the active condition.

These findings have both theoretical and methodological implications. First, because the very same motor actions were involved in both conditions and because the motor actions children performed in our task were not semantically related to the content of the objects studied, our results demonstrate that motor involvement alone, the process of physically performing an action, is not responsible for the active learning advantage, as suggested by studies adopting SPT paradigms. Secondly, our results speak in favor of adopting multimodal research paradigms that combine visual, verbal, and motor stimuli to better capture the multifaceted experience children have when engaged learning situations, especially those with learning difficulties. Indeed, the benefits of using supports based on visual and manipulative teaching aids with neuroatypical children are well-established and described in autism literature (Broun, 2004; Kluth & Darmody-Latham, 2003). Learning processes, after all, always involve the complex and dynamical interplay of different abilities, functions, contexts, and experiences. Such complexity needs to be accounted for also at the level of research design, to ensure validity of results and interpretations, for example, by extending this paradigm to include more real-world stimuli and tasks, tailored to match daily challenges, and opportunities experienced by children with autism and other special educational needs. For example, Ruggeri et al. (2019) designed a task to model real learning situations children encounter in school. Using a similar paradigm, children were tasked to learn the French labels for the same objects presented in our task. The researchers found that French labels were remembered more accurately when studied in an active as compared with a yoked condition. Based on this research, future studies might explore the role of active learning in learning new actions, words, or behaviors.

Given the many potential difficulties and resources presented by children in the autism spectrum, further investigations into their preferred learning strategies will help to better understand and improve current and novel teaching methods. In this regard, our study presents some limitations that should be taken into account and inform future research. As we focused on a rather limited subgroup of children with autism, that is, high-functioning children with very mild motor impairments and stereotypies, our findings have limited generalizability to the wider autism spectrum. Further research is needed to replicate findings in a sample of autistic children with greater variety of developmental profiles, abilities, and difficulties. Toward this aim, we are currently in the process of collecting a larger sample, encompassing a wider range of age and developmental disorders. On one hand, this would allow us to trace the emergence of the active learning advantage and compare the developmental trajectories of this effect in autistic and TD children. On the other hand, we are keen to explore whether and how general cognitive performance and symptom severity might impact the advantage of active learning and children's active study strategies.

To conclude, the present study takes a dimensional approach by bridging atypical, developmental and cognitive research. Our results highlight that high-functioning children with autism share the same memory advantage from active control of learning as TD children. This approach opens the way for studying *similarities* between typical and atypical groups, supporting inclusive classrooms while being as informative as stressing the differences between groups (Graham & Madigan, 2016). Our results suggest that offering children with developmental disorders concrete opportunities for self-generated, active learning experiences could help improve their learning (Haslam et al., 2017). Involving students in their own learning can also be beneficial for reducing problematic behaviors, while improving skill acquisition (Toussaint et al., 2016).

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ORCID iD

Valentina Fantasia https://orcid.org/0000-0003-2805-170X

Supplemental material

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