Journal of Experimental Child Psychology 103 (2009) 241–249

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Brief Report

When simple things are meaningful: Working memory strength predicts children's cognitive flexibility

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ARTICLE INFO

Article history:
Received 8 May 2008
Revised 12 January 2009
Available online 10 March 2009

Keywords:
Cognitive flexibility
Task switching
Working memory
Inhibition
Processing speed
Children

ABSTRACT

People often perseverate, repeating outdated behaviors despite correctly answering questions about rules they should be following. Children who perseverate are slower to respond to such questions than children who successfully switch to new rules, even after controlling for age and processing speed. Thus, switchers may have stronger working memory strength than perseverators, with stronger rule representations supporting both flexible switching and faster responses to questions. Alternatively, better inhibitory abilities may support switchers' faster responses by helping to resolve conflict. The current study tested these accounts using a new one-dimensional card sort. Even with all possible sources of conflict removed, switchers still responded faster than perseverators to questions about rules, supporting the graded working memory account.

Introduction

People are generally able to behave flexibly, breaking habits to deal with novel situations. However, sometimes people repeat old behaviors that are no longer appropriate. Such perseveration is apparent in older adults, children, prefrontal patients, and schizophrenics (Ashendorf & McCaffrey, 2008; Dunbar & Sussman, 1995; Rossell & David, 1997; Zelazo, 2004). For example, when 3-year-olds are presented with cards depicting blue trucks and red flowers, they will continue to sort them by the first rule they are given, color or shape, despite being instructed to sort them by the other rule (Kirkham & Diamond, 2003; Perner & Lang, 2002; Zelazo & Frye, 1998). However, they can answer simple queries about the rule they are failing to use. When asked where trucks go in the shape game they

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0022-0965/$ - see front matter
doi:10.1016/j.jecp.2009.01.002

correctly point to the red truck, but when given a blue truck they put it with the blue flower (Zelazo, Frye, & Rapus, 1996). Six-year-olds show similar behavior when asked to switch from deciding whether a speaker is happy or sad based on sentence content to deciding based on intonation, perseverating on content despite correctly answering queries about the rules for happy and sad intonation (Morton & Munakata, 2002b).

Why do perseverators succeed at answering simple queries about the rules of a game but fail to respond according to those rules? The problem appears to reflect a difficulty in resolving conflict. When queries contain information about the two conflicting dimensions (e.g., "Where do blue trucks go in the shape game?"), children perseverate just as they do when sorting cards (Morton & Munakata, 2002b; Munakata & Yerys, 2001). We contrast two explanations for this difficulty. The graded working memory account posits that the critical factor is the strength of working memory representations (Munakata, 2001). Children perseverate because their memories for the current rule are not strong enough to overcome the conflict in multidimensional questions and cards, but they can answer simple queries because weaker working memory suffices when there is no conflict (as simulated in Morton & Munakata, 2002a). The directed inhibition account, in contrast, posits that the critical factor is inhibitory ability (Kirkham & Diamond, 2003; Zacks & Hasher, 1994). Children perseverate because they cannot inhibit information about the first dimension in multidimensional questions and cards, but they can answer simple queries because there is no information to inhibit.

The graded working memory account makes a unique prediction: Switchers should answer simple queries faster than perseverators. Stronger representations of the current rule (e.g., shape) provide top–down support for task-relevant representations (e.g., truck, flower). The greater this support, the faster those task-relevant representations can reach the threshold for driving a response. This prediction has been confirmed (Cepeda & Munakata, 2007). Six-year-olds completed a computerized three-dimensional (3D) card sort (Fig. 1A) with stimuli varying along three dimensions: shape, color, and size (Deák, 2003). Children who flexibly switched between the rules and children who perseverated were equally accurate in answering simple queries (e.g., "In the shape game, what do you press when you see a cat?"), but switchers responded faster than perseverators even after controlling for age and processing speed. Thus, stronger representations of the current rule may support both flexible switching with conflicting stimuli and faster responses with nonconflicting stimuli. This result appears to challenge directed inhibition accounts.

Directed inhibition may nonetheless have helped switchers to respond faster to simple queries because two potential sources of conflict might have been resolved through inhibition. First, targets varied along all three dimensions (e.g., large blue cat), so ability to inhibit other dimensions of the target

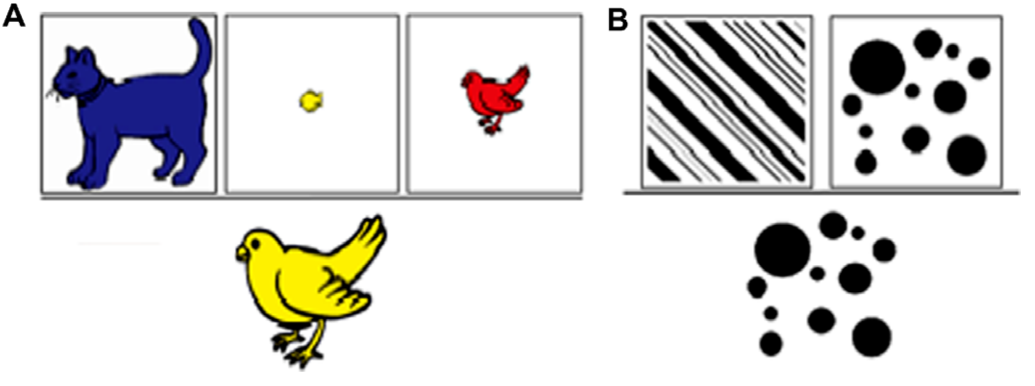

Fig. 1. (A) 3D card sort (adapted from Cepeda and Munakata, 2007). Participants selected one of the three target cards along the top row on each trial. Conflict stimuli matched each target on one dimension. No stimuli appeared on the lower half of the screen during simple query trials. (B) 1D card sort. Participants selected one of the two target cards on each trial. Stimuli exactly matched one of the two targets, so no inhibition of an irrelevant dimension was necessary to complete the task. No stimuli appeared on the lower half of the screen during auditory trials.

(e.g., to ignore that a blue cat is blue and focus on the fact that it is a cat) may have speeded reaction times. Second, responding to simple queries could require switching between modalities because simple queries were auditory but the targets were visual,[1] so the ability to inhibit the previous modality (i.e., to stop focusing on the auditory query and respond to visual stimuli) may have speeded reaction times. In addition, switchers' faster responses might reflect greater motivation or general cognitive abilities that aid performance on all tasks rather than working memory specifically.

The goal of the current study was to address the potential roles of inhibition, motivation, and general cognitive ability in the Cepeda and Munakata (2007) findings in order to more directly test the role of working memory strength in children's flexibility. We used the 3D card sort to classify children as switchers and perseverators, introduced a one-dimensional (1D) card sort with no information to inhibit to test our prediction about working memory strength, and adapted a probabilistic selection task (Frank, Woroch, & Curran, 2005) to distinguish benefits of greater working memory strength from greater motivation and general cognitive ability. The 1D card sort reduces each target to a single dimension of pattern (stripes or dots) that matches stimuli exactly, removing any benefit of inhibiting irrelevant target dimensions (Fig. 1B). Responses should still be speeded by stronger working memory because children are instructed to respond as fast as possible, and maintenance of the current rule should provide beneficial top–down support. The 1D card sort contrasts with standard measures of working memory, such as span tasks, that focus on capacity rather than working memory strength and likely tap multiple other processes (e.g., updating). The 1D card sort also presents simple queries in both auditory and visual modalities to test switchers' advantage when not switching between modalities (i.e., on visual queries). The probabilistic selection task relies on incremental long-term learning about the reward values of stimuli and, thus, should not show particular benefits from greater working memory strength.

The graded working memory account predicts that switchers should respond faster than perseverators to queries on the 1D task, whereas the directed inhibition account predicts that switchers and perseverators should be equally fast in responding because there is no conflicting information that could be inhibited. The graded working memory account further predicts that switchers and perseverators should be equally fast in incremental learning on the probabilistic selection task, whereas accounts based on greater motivation or general cognitive ability predict that switchers should learn faster.

Method

Participants

Participants in the study were 42 5- and 6-year-olds (mean age = 72.2 months, range = 69.1–75.4, 23 girls and 19 boys). An additional 19 participants were excluded because they did not meet the preswitch accuracy criterion of 70% (10), they had mixed switching performance (perseverating on one postswitch block but switching on the other) (4), they did not complete both processing speed tasks (2), or reaction time data for them were lost (3). Children were categorized by performance on the color and size blocks as *switchers* (83–100% correct, *M*s = 97.0% of color trials correct and 94.1% of size trials correct) or *perseverators* (0–25% correct, *M*s = 3.0% of color trials correct and 1.9% of size trials correct). Of the 42 participants, 30 (71%, 16 girls and 14 boys) perseverated and 12 (29%, 7 girls and 5 boys) switched. The mean age was 72.2 months for both perseverators (*SD* = 1.5) and switchers (*SD* = 2.1).

Materials and procedure

All participants completed tasks in the same order: box completion, offset reaction time, 3D card sort, 1D card sort, and probabilistic selection.

[1] Visual simple queries (e.g., a white bird of a size that did not exactly match any of the targets) were also presented but were not analyzed due to concerns about whether visual stimuli could truly be size neutral.

Processing speed

Two measures of processing speed were collected to provide a covariate for working memory strength. Both processing speed measures have low task set and cognitive demands that we believe make them relatively pure speed measures. Children were instructed to complete both tasks "as fast as you can." The first was a box completion task in which participants drew the fourth side of each box in an array of three-sided boxes (Salthouse, 1994). They practiced on a sheet containing 12 three-sided boxes and then completed as many boxes of a 5×7 array as possible in 30 s. The second was a computerized task in which participants placed one finger on a star in the corner of the screen and attempted to "pop" blue circles that appeared on the screen by pressing them. Reaction times to remove the finger from the star (finger–offset or finger–lift reaction time) were recorded across 10 trials.

3D card sort

The 3D card sort task was adapted from Cepeda and Munakata (2007) and based on Deák (2003). The top half of the screen contained three target images that were present throughout the task: a large blue cat, a small yellow fish, and a medium red bird (Fig. 1A). The task was divided into three blocks—shape, color, and size—in which participants were asked to match pictures by the current rule. Prerecorded video clips relayed instructions. For each block, participants were asked to identify all stimuli by the current dimension (e.g., "Can you press the cat?"), informed of the current rules (e.g., "In the color game, when you see a red one, press the red one"), asked three simple queries about the rules of the game (e.g., "In the size game, what do you press when you see a small one?"), and presented with 12 individual stimuli that matched each target on one dimension (e.g., a large yellow bird). No feedback or reminders were provided. Stimuli were always presented in a predetermined order that participants could not predict. All responses were made by pressing one of the targets, and reaction time was recorded on target press. Individual participants usually responded with the same hand and returned that hand to the same starting position between trials, but starting position differed across participants.[2]

1D card sort

The 1D card sort consisted of 20 trials of simple queries—10 auditory and 10 visual—about the rules for a pattern game. Children were encouraged to respond "as fast as you can" to encourage goal maintenance. The top half of the screen contained two target images that were present throughout the task: stripes and dots (Fig. 1B). Prerecorded audio clips relayed instructions. First, children were instructed to follow auditory requests in the absence of visual stimuli: "In the pattern game, when I say tap the stripes [dots], tap the stripes [dots]." Trials were presented in a random order with the verbal prompt, "In the pattern game, which do you tap for the stripes [dots]?" Next, children were instructed to respond to visual stimuli presented on the bottom half of the screen and exactly matching one target: "In the pattern game, when you see stripes [dots], tap the stripes [dots] at the top." Trials were presented in a random order, with images appearing at the end of the verbal prompt, "In the pattern game, which do you tap for this one?" All responses were made by pressing one of the targets, and reaction time was recorded on target press.

Probabilistic selection task

This two-alternative forced-choice task was presented as a game of "hide-and-seek" in which children tried to find animals behind one of two rocks on the computer monitor. One rock was correct on 90% of trials. The game ended when children selected the correct response on 7 of 10 consecutive trials or after 76 trials.

[2] Results were reliable despite any error added to the reaction time measurement from variations in starting position and hand used.

Data trimming and scores

Simple query reaction times were trimmed as in Cepeda and Munakata (2007), following a modified version of the Friedman and Miyake (2004) trimming procedure, to remove skewness caused by the small number of trials contributing to each mean. This procedure builds on prior work in this area and yields more easily interpretable results, and results were comparable to those of other skewness reduction procedures such as log transform. Participant means were trimmed by block (shape, color, and size) or modality (auditory and visual). Cases where participants responded correctly to only one query (2% of 3D card sort trials and 1% of 1D card sort trials) or responded in less than 200 ms (1% of 3D card sort trials and 0% of 1D card sort trials) were excluded without replacement. Cases more than 3 *SD* from the mean of the remaining participants were removed and replaced with a value exactly 3 *SD* from the new mean (9% of 3D card sort trials and 7% of 1D card sort trials). One box completion score and two offset reaction times greater than 3 *SD* from the mean of remaining scores were replaced with values exactly 3 *SD* from the new mean. A composite processing speed score was calculated from the z scores of each processing speed measure.[3] Switchers and perseverators did not differ in processing speed ($F < 1$).

Although the 1D card sort used 10 trials of each modality, continued maintenance of the rule should not be required with additional trials and performance should reflect habit memory more than active working memory. To maximize contributions from working memory, only the first half of each modality (five trials) was analyzed. Results are the same with cutoffs at any point within the first six trials of each modality, after which reaction times tended to plateau.

Results

Switchers responded faster than perseverators to 1D simple queries after controlling for age and processing speed, $F(1,37) = 7.6$, $p < .01$, $\eta^2 = .17$ (Fig. 2A), and simple query reaction time predicted whether children switched or perseverated better than age or processing speed (Table 1). There was no effect of modality ($F < 1$) and no interaction of modality and switching ($F < 1.5$). Switchers and perseverators did not differ in the time to learn the correct response on the probabilistic selection task (19.8 vs. 18.3 trials, $F < 1$). In addition, the main findings of Cepeda and Munakata (2007) were replicated; switchers responded to 3D simple queries faster ($M = 1229$ ms, $SD = 495.6$) than perseverators ($M = 1678$ ms, $SD = 813.2$) after controlling for age and processing speed, $F(1,36) = 4.6$, $p < .05$, $\eta^2 = .11$,[4] and 3D simple query reaction time predicted whether children switched or perseverated better than age or processing speed (Table 2).

Discussion

Switchers responded faster than perseverators to simple queries about the rule they should be using, even after controlling for age and processing speed and even with attempts to remove all conflict from the queries. These results confirm a unique prediction from the graded working memory account of perseveration: Switchers have stronger working memory representations than perseverators, providing greater top–down support for answering simple queries and, thus, speeding reaction times. Inhibitory abilities, motivation, and general cognitive ability cannot explain these differences because both the stimuli and the targets in the 1D card sort contained no information to inhibit, and switchers and perseverators learned the probabilistic selection task equally quickly.

[3] The measures were mildly but not significantly correlated ($r = .14$), as one might expect given the many methodological differences between these tasks (e.g., paper-and-pencil vs. computerized, motor demand differences). Results did not differ if processing speed measures were entered individually.

[4] There was an interaction between switch status and block, $F(2,72) = 3.6$, $p < .05$, such that the switcher advantage decreased across blocks. No such interaction was found in Cepeda and Munakata (2007), but the interaction of block and status is not different between the two studies ($F < 3$). There was an interaction between block and study, $F(2,118) = 4.7$, $p = .01$, such that reaction times on the shape block were slower in the current study, likely because children were younger and needed more time to get comfortable with the task.

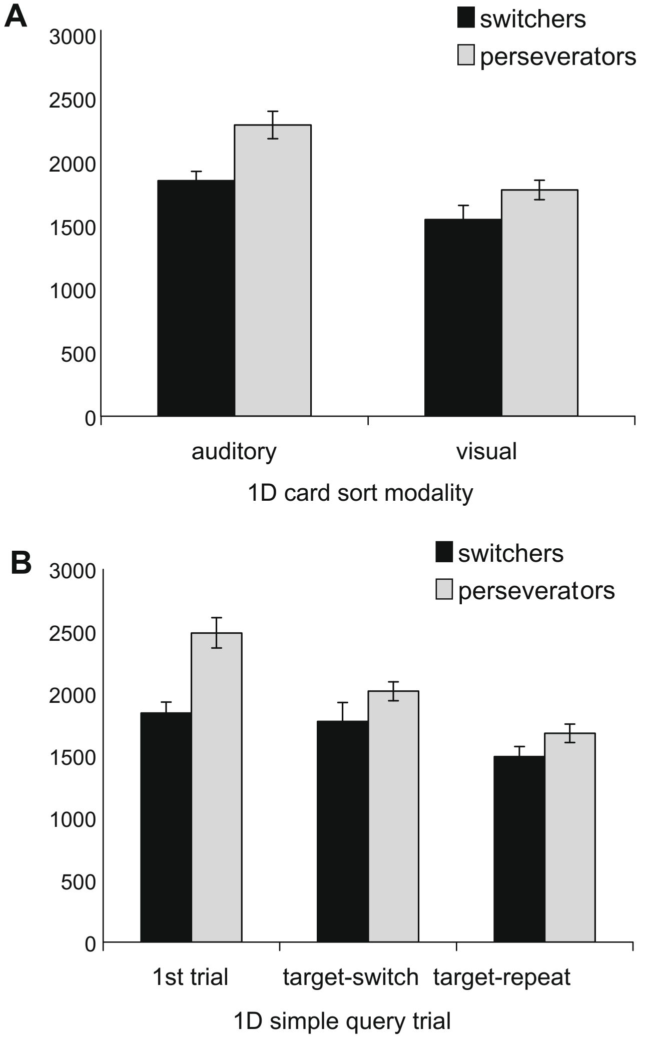

Fig. 2. (A) Switchers responded faster than perseverators to 1D simple queries even after controlling for age and processing speed. (B) Switchers responded faster than perseverators to 1D simple queries across the first trial, target–switch and target–repeat trials. Error bars represent 1 SEM.

Table 1
Hierarchical regression of card sort status on 1D simple query reaction time.

Independent variable	B	Exp(*B*)	Wald	*p*	R^2	R^2 change
Age	−0.022	0.979	0.01	.93	.00	
Processing speed	0.519	1.681	0.95	.33		.012
1D simple query reaction time	−0.004	0.996	6.14	.01		.299

Note. 1D simple query reaction time – hierarchical regression with Nagelkerke R^2. 1D simple query reaction time was predictive of ability to switch even after controlling for age and processing speed and was more predictive than processing speed.

Follow-up analyses suggest that revised inhibitory explanations are also unlikely. One argument is that switchers might benefit from inhibiting information that is no longer relevant (e.g., to switch from a task with three targets to a task with two targets, to switch from a task involving size to a task

Table 2
Hierarchical regression of card sort status on 3D simple query reaction time.

Independent variable	B	Exp(*B*)	Wald	*p*	R^2	R^2 change
Age	0.045	1.046	0.04	.84	.00	
Processing speed	0.933	2.541	2.47	.12		.012
3D simple query reaction time	−0.002	0.998	3.88	.05		.191

Note. 3D simple query reaction time – hierarchical regression with Nagelkerke R^2. 3D simple query reaction time was predictive of ability to switch even after controlling for age and processing speed and was more predictive than processing speed.

involving pattern). If this were the case, the link between switching and reaction times should be most prominent on the first trial. Another argument is that the 1D card sort involved switching between targets (i.e., stripes vs. dots), conferring a reaction time advantage for switchers. If this were the case, switchers should show an advantage on target–switch trials (e.g., dots after stripes) but not on target–repeat trials (e.g., dots after dots). Neither inhibitory prediction was corroborated: There was no effect of trial type (first trial, target–switch trial, or target–repeat trial) on switchers' advantage (Fig. 2B, $F < 2$). The profile of switchers' reaction time advantage is instead more consistent with greater working memory strength that benefits all trial types.

Our results do not rule out inhibitory explanations for all aspects of perseveration. However, some of the evidence used to argue for inhibition may be more consistent with graded working memory. For example, knowledge–action dissociations cannot simply reflect problems inhibiting prior actions because dissociations disappear when knowledge and action measures are equated for conflict (Morton & Munakata, 2002a; Munakata & Yerys, 2001). Dissociations could reflect inhibitory problems at a more representational level (e.g., a difficulty inhibiting attention to the first dimension) (Kirkham & Diamond, 2003), but graded working memory is sufficient to account for such dissociations (Munakata, 1998; Morton & Munakata, 2002a). Furthermore, only graded working memory accounts predict switchers' advantage on tasks with nothing to inhibit. Thus, although inhibition may play some yet to be discovered role in flexible behavior, graded working memory can explain many existing findings.

Our results provide a similar challenge for other theories of perseveration. The redescription account posits that children perseverate because they cannot describe stimuli in terms of a second dimension (Perner & Lang, 2002). The cognitive complexity and control theory (Zelazo & Frye, 1998) posits that children perseverate because they cannot represent a higher order rule structure necessary for switching between two sets of rules. These accounts seem unable to explain why switchers are faster than perseverators when there is nothing to redescribe and only one set of rules. Instead, working memory strength may support redescription and higher order rule representations because actively maintaining both dimensions may allow redescribing stimuli or switching between the rules for those dimensions. Thus, working memory strength should correlate with redescription and use of higher order rules and may link these factors to flexibility.

It may seem surprising that children bother to maintain a goal in answering nonconflict queries when 3-year-olds show decreased maintenance of task set after sorting cards that match targets exactly (Marcovitch, Boseovski, & Knapp, 2007). Our tasks may encourage more goal maintenance because the 3D card sort requires following a rule focused on one of three possible sorting dimensions, and the 1D card sort includes the instruction for children to respond "as fast as you can." In addition, 6-year-olds may have a greater tendency than 3-year-olds to actively maintain information. It also may seem surprising that more than half of 6-year-olds in this study perseverated on the 3D card sort given previous reports that 4-year-olds perform well on this task (Deák, 2003; Narasimham, Deák, & Cepeda, 2008). Key differences in the procedure include the lack of physical target boxes and stimulus cards, more preswitch trials, and single-dimension trials introducing the preswitch rule, all of which could have made the computerized task more difficult.

An additional test of the role of working memory in flexibility could come from direct manipulations of working memory strength if this could be manipulated independently of other working memory processes such as updating. Previous findings are suggestive. For example, 6-year-olds are more likely to perseverate when working memory demands are increased by reducing the frequency of rule reminders (Morton, Trehub, & Zelazo, 2003; see also Deák, Ray, & Pick, 2004).

Our results demonstrate that speed to answer nonconflict queries about the rules of a game predicts the ability to behave flexibly, suggesting that inhibition, redescription, and higher order representations cannot be solely responsible for flexibility. This finding supports the graded working memory account of perseveration, indicating that strength of working memory for a current rule is a significant contributor to cognitive flexibility that should be factored out before assessing the contributions of other factors. This is consistent with observations about the relationship between working memory and seemingly inhibitory abilities, such as controlling intrusive thoughts (e.g., Brewin & Beaton, 2002), resolving conflict among stimulus features (Egner & Hirsch, 2005), and overcoming prepotent responses in an antisaccade task (Unsworth, Schrock, & Engle, 2004), in the Stroop task (Kane & Engle, 2003) and in the absence of obvious memory demands (Stedron, Sahni, & Munakata, 2005). The fact that working memory may do more explanatory work than other factors in understanding cognitive flexibility also has implications for training and remediation; cognitive effort might be better applied to improving maintenance of the task at hand (e.g., focusing on skiing through a narrow path) rather than inhibition of unwanted information (e.g., focusing on the trees one does not want to hit). The graded working memory framework should prove to be useful for understanding these facets of cognitive flexibility.

Acknowledgments

This work was supported by grants from the National Institutes of Health (RO1 HD37163 and P50-MH079485). We thank Sara McQuiston, Joedy Hulings, and other members of the Cognitive Development Center (University of Colorado at Boulder) for useful discussions and assistance with this study.

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