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PAPER

Refining the understanding of inhibitory processes: how response prepotency is created and overcome

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Abstract

Understanding (a) how responses become prepotent provides insights into when inhibition is needed in everyday life. Understanding (b) how response prepotency is overcome provides insights for helping children develop strategies for overcoming such tendencies. Concerning (a), on tasks such as the day-night Stroop-like task, is the difficulty with inhibiting saying the name of the stimulus due to the name being semantically related to the correct response or to its being a valid response on the task (i.e. a member of the response set) though incorrect for this stimulus? Experiment 1 (with 40 4-year-olds) suggests that prepotency is caused by membership in the response set and not semantic relation. Concerning (b), Diamond, Kirkham and Amso (2002) found that 4-year-olds could succeed on the day-night task if the experimenter sang a ditty after showing the stimulus card, before the child was to respond. They concluded that it was because delaying children's responses gave them time to compute the correct answer. However, Experiment 2 (with 90 3-year-olds) suggests that such a delay helps because it gives the incorrect, prepotent response time to passively dissipate, not because of active computation during the delay.

Introduction

In the last 15 years evidence has accumulated from many tasks that young children have weak inhibitory control (e.g. Carlson, 2005; Davidson, Amso, Cruess Anderson & Diamond., 2006; Gerstadt, Hong & Diamond, 1994). Less attention has been given to how the need for inhibition is modulated. That is, 'How is response prepotency created?' and 'How can young children be helped to exercise better inhibitory control?'

Understanding how prepotency is created is important for four reasons. (1) It is a prerequisite for identifying which tasks require inhibition. For example, protracted debates have raged about whether tasks like the Dimension Change Card Sort task (Zelazo & Frye, 1998; Towse, Redbond, Houston-Price & Cook, 2000; Perner & Lang, 2002; Brooks, Hanauer, Padowska & Rosman, 2003; Kirkham, Cruess & Diamond, 2003; Hanania & Smith, 2010) or the Windows task (Samuels, Brooks & Frye, 1996; Russell, Hala & Hill, 2003; Simpson, Riggs & Simon, 2004; Carroll, Apperly & Riggs, 2007) require inhibition. (2) Understanding how prepotency is created in the laboratory can shed light on how and when prepotent response tendencies are created in 'the real world'. (3) It will shed light on whether during development children have different inappropriate prepotent response tendencies to inhibit. Inappropriate response tendencies might differ in content or intensity at different ages. (4) Finally, understanding how prepotency is created provides insight into ways in which inhibitory demands can be reduced or eliminated.

The final point leads to the second question, 'How can young children be helped to exercise better inhibitory control?' Situations in which executive functions are needed often call for two cognitive competences. In addition to inhibiting a prepotent response, children must engage in 'active computation' to determine the correct response (Gerstadt *et al*., 1994). Identifying what enables young children to succeed in these situations can provide guidance for parents and teachers. For example, finding creative ways to help a child wait (since saying 'wait' would be ignored) should help a child to complete the active computation needed before responding. Strategies that delay responding may also act to circumvent inhibitory demands by giving the prepotent, incorrect response time to rise to ascendancy and then

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passively dissipate, and so improve young children's success. Encouraging the use of such strategies might not only help young children, but could benefit older children who have developmental disorders (e.g. ADHD) or head injuries associated with inhibitory control deficits.

The experiments reported here investigated two ways in which the need for inhibition is modulated. Experiment 1 investigated how incorrect responses become prepotent and hence need to be inhibited. Experiment 2 investigated how a delay can help children avoid making prepotent response errors. This article was the product of a collaboration between two groups of researchers who had generated opposing hypotheses about how inhibition is modulated.

Experiment 1

How does a response become prepotent? Diamond and colleagues (Diamond, Kirkham & Amso, 2002; Gerstadt *et al.*, 1994) investigated how responses become prepotent in the day-night task. In this task children are instructed to say 'night' to a daytime image and 'day' to a night image. As noted above, like many executive-function tasks, there are two cognitive requirements: to compute a response using rules held in working memory (say 'night' to a white-sun card and 'day' to a black-moon card) and to inhibit a tendency to say what the stimuli portray. Gerstadt *et al.* (1994) demonstrated that young children make errors on the task not simply because of the memory demands. If the responses are kept the same but different stimuli are used, preschoolers succeed by saying 'day' to one abstract design and 'night' to another (same memory demand but no inhibitory demand). Diamond *et al.* (2002) went on to find that if the stimuli remain the same but different responses are taught (e.g. say 'dog' to day and 'pig' to night) even preschoolers succeed, though they must remember the two rules and avoid naming the stimuli. Thus, 4-year-olds *can* sometimes avoid naming what a stimulus portrays, *even* when they must hold two rules in mind.

Diamond *et al.* (2002) argued that 'the relation between the response-to-be-activated and the response-to-be-suppressed is key. What children of 4, or even 4½, years are unable to do consistently is to inhibit saying what a stimulus represents if the correct response is semantically related, and directly opposite, to the to-be-inhibited response' (p. 360). Such reasoning is consistent with findings from directed-forgetting studies where children are more likely to recall words they were instructed to forget if those words are semantically related to words they were instructed to remember (Harnishfeger & Pope, 1996; Lehman, Srokowski, Hall, Renkey & Cruz, 2003).

Simpson and Riggs (2005) questioned whether a semantic relation between the correct and to-be-inhibited response mattered. They argued that the two responses children plan to make in the day-night task are held in an activated state during the task. The problem, they reasoned, is that the incorrect response from this two-item response set is triggered by the stimulus and must be inhibited. This proposal is consistent with evidence from the color-word Stroop task showing that response set makes a distinct contribution to task difficulty (Dalrymple-Alford, 1972; La Heij, 1988; Milham, Banich, Webb, Barad, Cohen, Wszalek & Kramer, 2001; Proctor, 1978; Stirling, 1979).

Diamond *et al.*'s (2002) set of conditions could not distinguish the effect of semantic relation from membership in the task's response set because the two were perfectly correlated (Table 1). The standard day-night task would be difficult according to either a semantic relation or response set hypothesis. Conversely, the dog-pig variant would be easy, based on a lack of semantic relation between the to-be-inhibited and correct responses (e.g. night is unrelated to 'pig'), and because the stimuli ('day' and 'night') are not part of the response set ('dog' and 'pig' constitute the response set). Simpson and Riggs (2005) tried to dissociate semantic relation from response set by testing four conditions. In one condition, children were to say 'book' to a car image and 'car' to a book image. Car and book are not semantically related, so according to Diamond, this condition should be easy. The two responses ('car' and 'book') *are* part of the same response set and both need to be held actively in mind while performing the task. Seeing an image of a car would trigger the incorrect word in the response set ('car') and so Simpson and Riggs reasoned that this condition would be difficult.

Simpson and Riggs (2005) tested children 3 to 11 years old (Table 1). For older children (≥ 7-year-olds), the findings were clear: a strong response-set effect and no effect of semantic relation. For such children, what appeared to make responses prepotent in the day-night task was that the to-be-inhibited and correct responses were from the same response set. Whether these responses were semantically related seemed irrelevant. For younger children (3- to 5-year-olds) the findings were mixed. In addition to the same-response-set / not-semantically-related condition being difficult, young children also struggled with the different-response-set / semantically-related condition. The results were thus equivocal for the critical age range (ages 3–5 years).

More recently, Montgomery, Anderson and Uhl (2008) obtained data from preschoolers consistent with Simpson and Riggs' response-set hypothesis. They investigated the effect of response set and semantic relation in two experiments (Table 1). Crucially, they found that a same-response-set / not-semantically-related condition was difficult, while two different-response-set / semantically-related conditions were easy. However, (a) neither experiment included an easy baseline condition (where items are from different response sets and are not semantically related), (b) performance in the key same-response-set / not-semantically-related condition was not quite as poor as in the standard day-

Table 1 *Difficulty of day-night task conditions used in Diamond et al. (2002), Simpson & Riggs (2005), Montgomery et al. (2008), and this article as predicted by the response-set and semantic-relation hypotheses and as empirically found*

Condition	Rules (see → 'say')	Response set	Semantic relation	Findings re: Difficulty for 4-year-olds
Diamond *et al.* (2002)				
Standard Condition		same	related	hard 53% correct
Same-response-set/semantically-related	day image → 'dog' night image → 'day'			
Different-response-set/no-semantic-relation	day image → 'dog' night image → 'pig'	different	unrelated	easy 92% correct
Simpson & Riggs (2005)				
Same-response-set/semantically-related	red → 'blue' blue → 'red'	Same	related	hard 78% correct
Different-response-set/no-semantic-relation	day image → 'dog' night image → 'pig'	different	unrelated	easy 86% correct
Same-response-set/no-semantic-relation	car image → 'book' book image → 'car'	Same	unrelated	hard 78% correct
Different-response-set/semantically-related	black → 'green' white → 'yellow'	different	related	hard 70% correct
Montgomery *et al.* (2008)				
Experiment 1				
Standard Condition		same	related	hard 65% correct
Same-response-set/semantically-related	day image → 'night' night image → 'day'			
Different-response-set/semantically-related	night image → 'day' girl image → 'boy'	different	related within-trial	easy 95% correct
Experiment 2				
Same-response-set/semantically-related	pants image → 'shirt' shirt image → 'pants'	same	related	hard 68% correct
Different-response-set/semantically-related	pants image → 'shirt' fork image → 'spoon'	different	related within-trial	easy 95% correct
Same-response-set/no-semantic-relation	pants image → 'fork' fork image → 'pants'	same	unrelated	hard 74% correct

This article				Predicted difficulty based on: Response set	Predicted difficulty based on: Semantic relation
Standard condition (difficult baseline):		same	related	hard	hard
Same-response-set/semantically-related	day image → 'night' night image → 'day'				
Bird-hat /fish-cup (easy baseline):		different	unrelated	easy	easy
Different-response-set/no-semantic-relation	bird image → 'hat' fish image → 'cup'				
Car-book:		same	unrelated	hard	easy
Same-response-set/no-semantic-relation	car image → 'book' book image → 'car'				
Dog-cat/hand-foot:		different	related within-trial	easy	hard
Different-response-set/semantically-related	dog image → 'cat' hand image → 'foot'				
Table-boy/girl-chair:		different	related between-trials	easy	easy
Different-response-set/semantically-related between-trials	table image → 'boy' girl image → 'chair'				

night task, and (c) in neither experiment was reaction time assessed. The studies of Diamond and of Simpson and Riggs had measured both accuracy and reaction time. Montgomery *et al*. (2008) measured only accuracy and so the possibility of speed–accuracy trade-offs masking the difficulty of semantically-related conditions could not be excluded. In Experiment 1 we carried out a more definitive test of the two rival hypotheses of Diamond and of Simpson and Riggs – with half the data collected by each research group.

Five day-night conditions were tested. See Table 1 for a summary of conditions and predictions. Two conditions were included to provide baseline performance: the standard condition for poor performance; and a different-response-set / no-semantic-relation condition (to-bird-say-'hat', to-fish-say-'cup') for good performance. Two conditions were included to distinguish between the two hypotheses: A same-response-set / no-semantic-relation condition (to-book-say-'car', to-car-say-'book') was predicted to be hard by Simpson and Riggs as the stimuli and responses were from the same response set, and easy by Diamond as there was no semantic relation between each stimulus and response. In contrast, a different-response-set / semantically-related condition (to-dog-say-'cat', to-hand-say-'foot'), was predicted to be easy by Simpson and Riggs as the stimuli and responses were from a different response set, and hard by Diamond as each stimulus and response was semantically related.

The final condition was included to investigate whether children sometimes had difficulty remembering the day-night rules. In Simpson and Riggs (2005), uncertainty about the role of semantic relation arose because the different-response-set / semantically-related condition was difficult for young children. A memory test suggested that children struggled to remember the rules in that condition which presented two arbitrary pairings of semantically related items (to-black-say-'green', to-white-say-'yellow'). Perhaps poor performance in this condition was not due to inhibitory difficulty, but because children struggled to remember the rules? Thus the final condition was a different-response-set/semantically-related condition with a greater memory load. In this condition the semantic relation was between-trials, rather than within-trial as in the other semantically-related condition. To an image of a table, children were to say 'boy', which was semantically related to the other stimulus (girl). To the girl stimulus, children were to say 'chair', which was semantically related to the other stimulus (table). Because the semantic relation was between-trials, Diamond predicted that young children would have no difficulty (table was not semantically related to boy). Simpson and Riggs, too, predicted that this would be easy because the names of the images ('table' and 'girl') were not part of the response set. However, if memory load were a problem, then young children might have difficulty here.

Methods

Participants

Participants were 40 children (20 girls and 20 boys) aged between 3 years, 9 months and 4 years, 3 months (mean = 3.97 years). They spoke English as a first language and none had behavioral or educational problems (based on teacher report). Half (10 girls and 10 boys) attended a nursery in a rural location in the County of Suffolk, England. They were all white, and from working- and middle-class backgrounds. The other 20 children attended preschools in Vancouver, BC, Canada. Most were white, six were Asian, and all were from middle-class backgrounds. Each child was tested on all conditions.

Materials

The stimuli were 10 images (22 × 15 cm; see Figure S1 in online Supplementary Material) presented with Presentation© software (by Neurobehavioral Systems, Inc.) on a laptop PC. Audacity© voice recorder software application (Audacity Audio, Inc.) recorded response time (RT). A beeping sound from the laptop marked the onset of each trial.

Procedure

Each child received the five conditions spread across three test sessions. The dependent measures were accuracy and RT. Multiple sessions were used to avoid fatigue and carry-over effects from other conditions of the same tasks. All three sessions were delivered within a period of one week. Sessions 1 and 2 contained two day-night conditions separated by a filler task. The final session contained a single day-night condition. There were five presentation orders so that between children each condition appeared first to fifth equally often. All five conditions were presented in the same way. The only differences across conditions were the stimuli and responses. Children were given up to six practice trials with feedback for each condition. When children responded correctly on two consecutive practice trials they progressed to the test trials. The testing protocol for each condition consisted of 16 trials in pseudo-random order. Stimuli remained on the screen until the child answered. No feedback was given on test trials.

Results

Data were analyzed with trial nested within condition for each participant. Within-participant comparisons were made across conditions since each participant received all conditions. Thus, accuracy (dichotomous at the individual trial level) was analyzed using a generalized estimating equation with a binary logistic model to account for correlation in repeated binary measurement of individuals. RT (a continuous variable) was analyzed using a linear mixed model that took into account multiple trials per participant. There was no effect of gender.

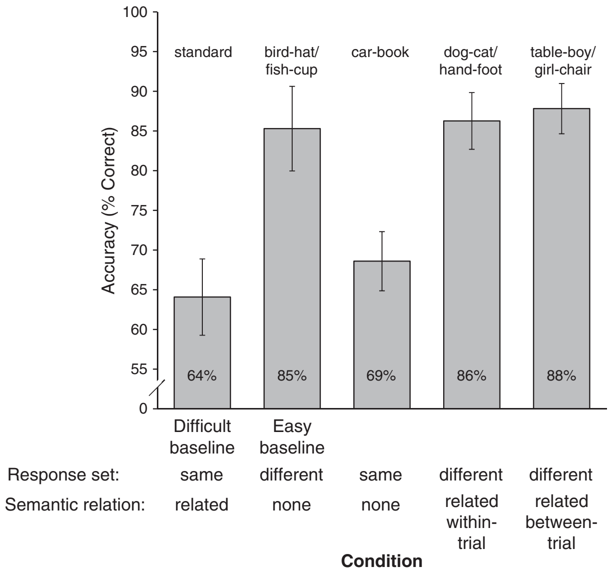

Figure 1 *The accuracy of responding in the conditions from Experiment 1 for the day-night tasks. Error bars show the standard error of the mean.*

Accuracy

Accuracy was low (only 64% correct) in the standard (difficult baseline) condition and in the book-car condition (only 69% correct; see Figure 1). Accuracy was high (≥ 85% correct) in all other conditions. Consistent with the Simpson and Riggs hypothesis, in both conditions where the to-be-inhibited response was a member of the response set, and *only* in those two conditions, children performed poorly. In all conditions where the to-be-inhibited response was *not* a member of the response set for the task, children performed well.

Generalized estimating equation analyses showed a significant difference in accuracy among the five conditions [$X^2(4, N = 40) = 24.77$, $p < .001$] and a significant effect of response set. Children made significantly more errors in same-response-set conditions (standard and book-car) than in different-response-set conditions (bird-hat/fish-cup; dog-cat/hand-foot; and table-boy/girl-chair) [$X^2(1, 40) = 17.73$, $p < .001$, odds ratio = 2.70]. The odds ratio indicates that children were 2.7 times more likely to err on a trial in the standard and book-car conditions than in the three other conditions. There was no significant effect of semantic relation between the to-be-inhibited and correct responses.

Bonferroni pairwise comparisons showed that (a) accuracy in the book-car condition did not significantly differ from the standard condition, (b) accuracy in each of the other three conditions did not significantly differ among themselves, but (c) accuracy in the book-car and standard conditions was significantly worse than accuracy in each of the other three conditions [book-car versus bird-hat/fish-cup: $t(39) = 2.68$, $p = .03$; book-car versus dog-cat/hand-foot: $t(39) = 2.15$, $p = .03$; book-car versus table-boy/girl-chair: $t(39) = 3.08$, $p < .006$); standard condition versus bird-hat/fish-cup: $t(39) = 3.40$, $p < .005$; standard condition versus dog-cat/hand-foot: $t(39) = 3.55$, $p < .001$; standard condition versus table-boy/girl-chair: $t(39) = 3.80$, $p < .001$].

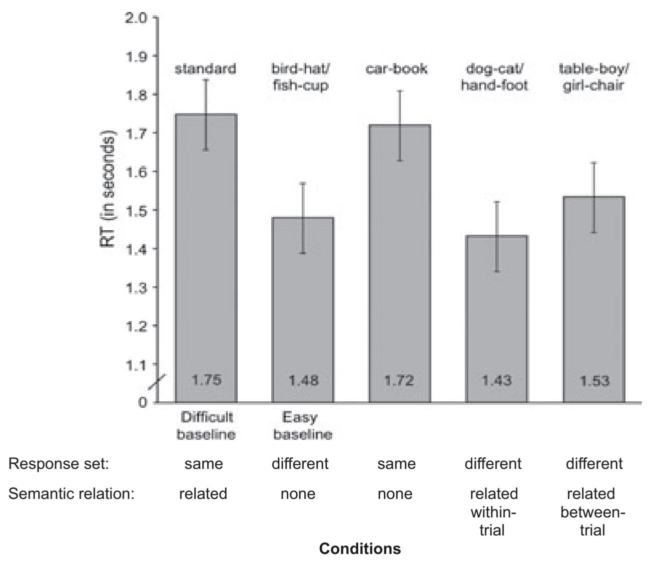

Figure 2 *Reaction times for the five day-night task conditions from Experiment 1. Error bars show the standard error of the mean.*

Reaction times

RTs told a similar story (Figure 2). RTs were analyzed if they met four criteria: (a) the response was audible, (b) the response was correct, (c) RT > 200 ms (otherwise the response would be too fast to be in reaction to the stimulus), and (d) RT was ≤ 2 standard deviations longer or shorter than the child's mean RT for that condition. Very few trials were omitted because they were inaudible (< 2%) or because RT was aberrantly long or short (< 1/10 of 1%). The mean RTs for the conditions in which the stimuli and eligible responses belonged to the same response set (1.75 s for the standard condition and 1.72 s for the book-car conditions) were longer than RTs when responses and stimuli were *not* from the same response set (which varied from 1.43 to 1.53 s).

Using a linear mixed model controlling for order and location, there was a significant difference in RT among the five day-night conditions [$F(4, 40) = 39.94$, $p < .001$]. There was a significant effect for whether the stimuli and responses belonged to the same response set. Children took significantly longer to respond in conditions where all belonged to the same response set (the standard and book-car conditions) than conditions where they did not (bird-hat/fish-cup; the dog-cat/hand-foot; and table-boy/girl-chair: $F(1, 40) = 157.39$, $p < .001$). There was no significant effect on speed of responding for whether there was a semantic relation between the to-be-inhibited and correct responses (the standard and dog-cat/hand-foot conditions versus the car-book, bird-hat/fish-cup and table-boy/girl-chair conditions).

Bonferroni pairwise comparisons showed that (a) RTs on the standard and book-car conditions did not differ significantly, (b) RTs on the other three conditions did not differ significantly, and (c) RTs in the standard and book-car conditions were significantly longer than in other conditions [standard versus dog-cat/hand-foot, $t(34) = 3.16$, $p < .01$; standard versus bird-hat/fish-cup, $t(34) = 2.69$, $p < .02$; book-car versus dog-cat/hand-foot, $t(34) = 2.29$, $p < .04$; book-car versus table-boy/girl-chair, $t(34) = 2.06$, $p < .04$].

There was a significant interaction between location and condition. Canadian children showed a smaller RT difference between conditions than British children: $F(1, 40) = 75.12$, $p < .001$. However, the same pattern of between-condition differences was found at both sites (though less pronounced in Canada), and the differences between book-car and standard conditions and the other conditions were significant for both sites.

There was also a significant effect of order on condition: $F(4, 40) = 14.69$, $p < .001$. When the easy baseline (bird-hat/fish-cup) followed the two hard conditions (the book-car and standard conditions), (a) children performed 8.8 times better [X^2 (1, 40) = 5.30, $p < .03$] on the easy baseline condition than when that condition followed immediately after only one of the hard conditions (the standard condition), and (b) children performed 5.6 times better [X^2 (1, 40) = 6.32, $p < .01$] on the easy baseline condition than when that condition came first (Order 3). Perhaps the difficult conditions helped children focus so that when they were tested on both hard conditions just before the easy baseline they did better on the easy baseline. In any event, the significant differences between the conditions held controlling for both location and order of conditions.

Discussion

The data revealed a clear, consistent pattern. Children needed more time to respond and were more likely to err when the word they had to inhibit (what the image portrayed) was from the same response set as the word they were supposed to say. The presence of a semantic relation between what an image depicted and the word they were to say had no effect on performance. There was no evidence for a speed–accuracy trade-off. The presence of a semantic relation made children neither slower nor less accurate. These results support the hypothesis of Simpson and Riggs and disconfirm that of Diamond.

We suggest that young children struggled with the different-response-set / semantically-related condition in the Simpson and Riggs (2005) study because of its greater memory load and not because of the condition's inhibitory demands. When we eliminated the extra memory requirement in the present study (the dog-cat/hand-foot condition), young children performed splendidly. Overall, the data from Diamond *et al.* (2002), Simpson and Riggs (2005), Montgomery *et al.* (2008), and the current study make it clear that a response is prepotent when it is from the response set for a given task condition, and not because it is semantically related to the image used on that trial.

Experiment 2

This experiment investigated the second of the questions outlined in the introduction 'How can response prepotency be overcome?' Gerstadt *et al.* (1994) observed that those 3½- and 4-year-olds who took longer to respond on the day-night task performed better; and within-child, on trials where children took longer, they performed better. Diamond *et al.* (2002) found that imposing a delay after the stimulus was shown (by the experimenter chanting something) improved 4-year-olds' performance. However, imposing that delay between trials (by the same chanting), and therefore before children knew which stimulus would be shown, did not. Diamond *et al.* reasoned that a delay after stimulus presentation helped because children could use that extra time to actively compute the answer. A delay between trials did not help because, without knowing which stimulus would be shown, children did not know what to compute during the delay.

Simpson and Riggs (2007) proposed an alternative hypothesis. They suggested that maybe children were not using the extra time to compute anything. Perhaps what happened was that the incorrect response (naming the image), being prepotent, had a shorter rise time and raced to the response threshold before the correct response (following the task rule) was computed. Imposing a delay after stimulus presentation gave that incorrect response time to passively dissipate and the correct response time to become ascendant. Imposing a delay between trials, of course, was not useful because only after a stimulus was displayed did activation of any response begin.

Simpson and Riggs (2007) investigated this with a go/no-go task. In go/no-go tasks, the prepotent response is made on go trials and withheld on no-go trials. In their box-search task, children were shown a number of boxes and told to open boxes with one cue on the lid (go trials) and leave shut boxes with another cue on the lid (no-go trials). Young children tend to open boxes and have difficulty inhibiting that prepotent response on no-go trials (Livesey & Morgan, 1991; Simpson & Riggs, 2007). Simpson and Riggs used the box-search task because it has a property not shared by the day-night task. In the box-search task the stimulus that activates the prepotent response (the box) is different from the stimulus that specifies whether to respond (the cue on the box lid). In the day-night task the image both triggers the prepotent response and specifies how to respond.

Simpson and Riggs capitalized on this property of the box-search task by initially showing children the box without a cue, waiting 2 seconds and only then placing the cue on the lid – giving the prepotent response time to fade without children yet knowing whether to respond. (In the box-search task children must compute whether or not to respond: unlike in the day-night task where the computation selects between two responses.) According to Simpson and Riggs' 'passive-dissipation' hypothesis, the couple of seconds' delay improved no-go performance because activation of the incorrect prepotent response had time to fade. Consistent with this prediction, children made fewer go errors on no-go trials in the delay condition.

Children might, however, have used the delay to remind themselves of the rules or to reflect on their adherence to them in previous trials. Such reflection on the rules could have improved no-go performance, and would be consistent with Diamond's 'active-computation' hypothesis (i.e. delay helps children conduct mental computations that aid performance). Thus, children's success in the Simpson and Riggs (2007) delay condition could be consistent with either their passive-dissipation hypothesis or Diamond's active-computation hypothesis. The question of which hypothesis best explained why delay improves inhibitory performance remained open.

To investigate these alternative hypotheses we compared performance in three box-search conditions. The immediate and delay conditions were identical to those used by Simpson and Riggs (2007). In the critical third condition (the distraction-during-delay condition), on each trial a box was presented before the cue. However, unlike the delay condition, children were given a simple task to perform during the delay. In the delay condition, it is conceivable that children could use the delay to reflect on the rules (i.e. do active computation). In the distraction-during-delay condition, however, because children were occupied during the delay, such computation was impossible. Hence, Diamond predicted that giving children something to do during the delay would eliminate any benefit from the delay. If, however, delay aids performance because it gives the prepotent response time to passively fade, then whether or not children were occupied during the delay would not matter. Hence, Simpson and Riggs predicted that no-go performance would be as good in the distraction-during-delay condition as in the delay condition.

Method

Participants

Ninety children (between 3 years, 0 months and 3 years, 11 months) took part in Experiment 2 (45 girls and 45 boys). They spoke English as a first language and none had behavioral or educational problems. The majority of children were from a working-class background and all attended a nursery in an inner city borough of London, England.

Materials

Two strips of cardstock were used (each 55 mm wide × 750 mm long; Figure S2). Eight white boxes (each 40 mm cubed with lids 55 mm) were attached to one strip of cardstock, and another eight boxes were attached to the other strip. This arrangement made it easier to ensure that the boxes were correctly ordered and easy to move. The 'go' cue was a blue square and the 'no-go' cue was a red triangle (each 40 mm on all sides). A cue was either fixed to, or placed on, each box lid. On go trials the box contained a sticker; on no-go trials the box was empty. A third strip of cardstock (60 mm wide × 800 mm long) was used so all eight boxes attached to a strip could be covered and then revealed one at a time.

Procedure

In the immediate condition, the experimenter showed the child two boxes and explained that if there was a square on a lid there was a sticker inside the box, but a triangle on the lid meant there was no sticker inside. Children were told to open the boxes with a square on the lid to win stickers, but to leave boxes with a triangle shut because they were empty. Children were reminded of the rules before the practice trials began (e.g. 'Are you ready to find the stickers? Remember, open the boxes with squares on top – they have stickers inside; leave the boxes with triangles on top shut – they are empty.'). Before testing, children were given four practice trials with feedback. In the test session, 16 trials were presented in a pseudo-random order with eight go and eight no-go trials with no verbal feedback. Children were given 3 s to open a box. If they did not respond in that time, the response was recorded as a 'no-go', and the experimenter revealed the next box. After the first eight trials, the next eight boxes were placed on the table, covered by the long sheet of cardstock, again displaying each box one at a time.

In the two delay conditions, before the practice trials began, children were told 'You mustn't open the box until I put the shape on top because only when the shape is on can you tell if there is a sticker inside. Don't open any box until I put a shape on top. Remember, open the boxes with squares on top – they have stickers inside; leave the boxes with triangles on top shut – they are empty.' Once a box was revealed, the experimenter waited 2 s before placing the cue on the lid. Hence, the delay was 2 s. In addition to the other instructions, in the distraction-during-delay condition children were told, 'Guess which hand the shape is in. After that I'll put the shape on the box. Are you ready to guess which hand the shape is in and find the stickers? After revealing a new box, the experimenter held out her clenched fist, palm down, next to the newly exposed box and asked the child to 'Guess which hand?' After the child guessed, the experimenter first opened the 'picked' hand, then the other, and affixed the cue to the lid of the box.

In both delay conditions, if a child reached to open a box before the cue was placed on the lid, the experimenter stopped the child (coded it as an error) and reminded the child it was important not to open the box until the cue was placed on the lid. The experimenter then waited a further 2 s before placing the cue on the lid. An error was recorded if (a) a child attempted to open the box lid during the delay, (b) a child attempted to open the box lid *after* the delay on a no-go trial, or (c) a child did not attempt to open the box lid on a go trial.

Results and discussion

Analyses of accuracy, using a generalized estimating equation, showed an overall significant difference between go and no-go trials [$X^2(1, N = 76) = 82.37, p < .001$]. Children were significantly more likely to err on no-go than on go trials (18.9 times more likely).

Accuracy on no-go trials was low in the immediate condition (51% correct) and higher in both delay conditions (delay: 78%, distraction-during-delay: 85%; see Figure 3). Generalized estimating equation analyses

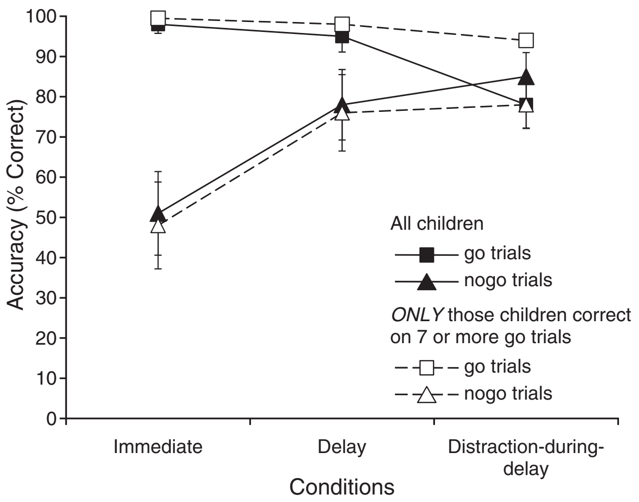

Figure 3 *Box-search task performance in Experiment 2. Solid lines, accuracy of responding on go (black squares) and no-go (black triangles) trials in the three box-search task conditions. Dashed lines, accuracy of just those children who performed above chance on go trials (go trials: white squares; no-go trials: white triangle). Error bars show the standard error of the mean.*

showed a significant difference among the three conditions in no-go performance [$X^2(2, N = 76) = 9.52, p < .01$]. Children in the immediate condition were more likely to err on no-go trials (less likely to inhibit the impulse to open the box) than children in either the delay condition [3.4 times more likely to err (odds ratio), $X^2(1, N = 76) = 5.89, p < .02$] or the distraction-during-delay condition [3.9 times more likely to err, $X^2(1, N = 76) = 8.12, p < .005$]. No-go performance did not differ between the two delay conditions.

Unexpectedly, there was also an effect of condition on go performance [$X^2(2, N = 76) = 10.85, p < .005$]. Accuracy was very high on go trials in the immediate (98% correct) and delay (95% correct) conditions, but lower in the distraction-during-delay condition (78% correct). Children in the distraction-during-delay condition were significantly more likely to err on go trials (more likely to fail to open the box when they should have) than children in the immediate condition [14.9 times more likely to err, $X^2(1, N = 76) = 7.07, p < .01$] or the delay condition [5.1 times more likely to err, $X^2(1, N = 76) = 2.31, p = .13$]. Go performance did not differ significantly for the immediate and delay conditions.

Distracting children during the delay did not reduce the benefit of a delay on no-go performance. This would seem to favor passive-dissipation over active-computation. However, the relatively low accuracy on go trials in the distraction-during-delay condition raises the possibility that the distraction caused children to forget what they had to do; hence they were great at doing nothing (no-go trials) but not so good when they were supposed to respond (go trials).

Of the 30 children in the distraction-during-delay condition, 20 performed significantly above chance on go trials (they were correct ≥ 7 out of 8 trials – binomial distribution, $p < .04$). When no-go performance in the distraction-during-delay condition for *only these children* was compared with children in the immediate condition, no-go performance was still significantly better in the distraction-during-delay condition [$X^2(1, N = 48) = 7.851, p < .005$]. Children with good go performance in the distraction-during-delay condition made fewer no-go errors (3.8 times less) than children in the immediate condition. Thus, those children in the distraction-during-delay condition who did not lose track of their intention to open boxes were better able to avoid box opening on no-go trials than those children not experiencing the delay (in the immediate condition).

In both delay conditions the box was presented first and the cue placed on it after the delay. Perhaps this made the cue more salient. Might better performance in the delay conditions have been due to children observing the experimenter placing the cue on the box lid (which happened only in the delay conditions)? This interpretation seems unlikely given children's poor go performance in the distraction-during-delay condition. Increased salience of the cue should have helped performance on all trials. It is not consistent with poorer performance on go trials in the distraction-during-delay condition. Neither would increased cue salience be able to account for why delay improves performance on the day-night task (Diamond *et al.*, 2002). One would need one explanation for better performance with delay on the box-opening task and a different explanation for better performance with delay on the day-night task. The passive-dissipation hypothesis provides a parsimonious explanation for why delay improves performance on both tasks.

The box-search and day-night tasks differ in several ways. It is a strength of the passive-dissipation hypothesis that it can account for the effect of delay on both these tasks despite their differences. One difference is that children select between two responses in the day-night task, but merely whether or not to respond in the box-search task. Some (e.g. Nigg, 2000) would claim that these two tasks assess different aspects of inhibition: 'behavioral inhibition' in the box-search task and 'cognitive interference' in the day-night task. While the non-inhibitory demands of the two tasks do differ, others emphasize the similarity of their inhibitory demands because both involve inhibition of a *prepotent* response rather than interference between *equivalent* responses (e.g. Friedman & Miyake, 2004; Verbruggen, Liefooghe & Vandierendonck, 2004; Verbruggen, Liefooghe, Notebaert & Vandierendonck, 2005). Other differences between the two tasks include the previously discussed separation of the cue and trigger stimulus in the box-search task but not in the day-night task. Also, the day-night task requires inhibition of a verbal response and the box-search task inhibition of a manual response.

Overall, the results of Experiment 2 show that performance on no-go trials was better after a delay, even when children could not use that delay for activate computation. Looking only at those children who accurately opened the box on all, or all but one, of the go trials in the distraction-during-delay condition, no-go performance was still significantly better than for those children tested without a delay. Better performance on no-go trials after a delay is consistent with both the active-computation and passive-dissipation hypothesis. However, better performance on no-go trials after a delay where active computation was prevented is consistent only with the passive-dissipation hypothesis.

General discussion

How is response prepotency created?

The data are absolutely clear. In two conditions of the day-night task where the names of the two images were included in the response set (making them valid responses – held active during the task) children had difficulty inhibiting those names. They took longer and made more errors. In the three conditions where the names of the images were not valid responses for the task, children had little difficulty; they responded faster and made fewer errors. We suggest the factor that determines the prepotency of a response (at least for the day-night task) is whether that response is valid for the task. If the name of one image (e.g. 'car') is the required response when the other image (e.g. book) is shown, children have difficulty. This is true even if the name of the image bears little or no semantic relation to the valid response (car is unrelated to book). In contrast, when the name of the image is never a valid response on the task, the task is easy irrespective of any semantic relation. Simpson and Riggs' response-set hypothesis was supported.

This pattern of findings (a response set effect but no semantic effect) is consistent with other developmental studies using the day-night task (Montgomery *et al.*, 2008; Simpson & Riggs, 2005), a cross-modal variant (Hanauer & Brooks, 2005), and with studies of the classical Stroop task in adults (Dalrymple-Alford, 1972; La Heij, 1988; Milham *et al.*, 2001; Proctor, 1978; Stirling, 1979). A response set effect has also been observed in developmental tasks involving actions on artifacts (Simpson & Riggs, 2007) and imitation (Simpson & Riggs, 2011).

Crucially these results show that a response *becomes* prepotent because of task conditions. In general, children can avoid saying 'book' when they see an image of a book. They have difficulty only when they are primed to say 'book' on the task. Responses become prepotent because of the child's intention to produce them at some point during the task (see Hommel, 2000, for a similar analysis of tasks with adults). It is the rule structure of the task that causes the wrong response to be triggered and young children's inhibitory weaknesses to be exposed.

What does this tell us about how prepotency operates outside the laboratory? It is unlikely to operate in *exactly* the same way – children rarely plan to make one of two responses and then wait to see which is triggered. Nevertheless *similar* processes may operate. Children may know how they should behave, but if something in the environment reminds them of another action (e.g. seeing crayons makes them think of drawing), that action may become primed. Under such circumstances young children, with weak inhibitory control, may incorrectly make the primed response even though they know better.

How can response prepotency be overcome?

Children are more likely to avoid making an incorrect prepotent response if there is more time between presentation of the triggering stimulus and when they respond. This has been shown using a variety of inhibitory tasks: go/no-go (Jones, Rothbart & Posner, 2003), theory of mind (Heberle, Clune & Kelly, 1999), day-night (Diamond *et al.*, 2002), and a Piagetian search task (Rivière & Lécuyer, 2003). Diamond and colleagues (2002) hypothesized that more time helps because young children need time to compute their answer. Simpson and Riggs (2007) hypothesized that more time helps because it allows the prepotent response (with a faster rise time) to fade, enabling the correct answer to compete more successfully. The results of Experiment 2 support Simpson and Riggs' passive-dissipation hypothesis. In the distraction-during-delay condition children resisted opening boxes on no-go trials. They did this despite not being able to compute anything during the delay because they were occupied with a guessing game. The guessing game may have been too distracting for some children, impairing performance even on go trials. Nevertheless, even among those children with good go performance, the imposition of the delay helped them to resist opening boxes on no-go trials. Good no-go performance in the distraction-during-delay condition is consistent with the passive-dissipation hypothesis but not with the active-computation hypothesis.

The proposed process can be seen at work in a video of a child performing the standard day-night task and the 'ditty' variant of it (Diamond *et al.*, 2002; see http://www.devcogneuro.com/videos/daynight3.mov). The 4-year-old in the film errs in the standard condition, but always corrects himself. Clearly there seems to be no problem with his memory or understanding of the rules. In the ditty variant, he performs flawlessly, yet the video shows the child giving his full attention to the experimenter as she chants the ditty. Only after the ditty is over does he appear to begin his deliberation of which

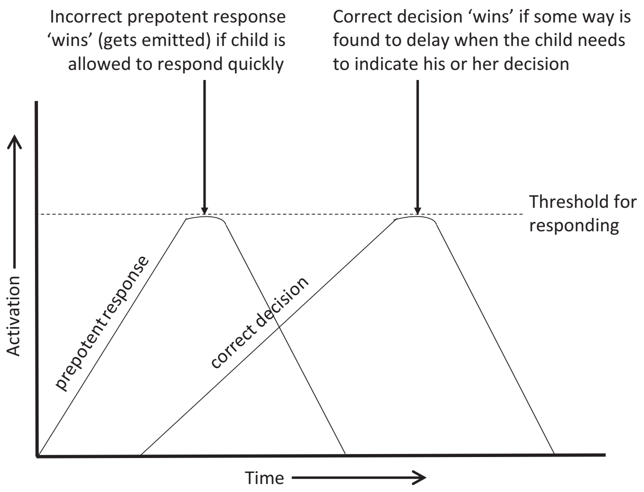

Figure 4 *Passive-dissipation model showing how delay can improve performance on inhibitory tasks.*

response to make. Thus the child does not appear to be using the time while the experimenter is chanting to compute the answer. Passive dissipation of the incorrect, prepotent response would seem to be the explanation.

With current evidence supporting the passive-dissipation hypothesis, we outline a model for this process that can be tested in future investigations (Figure 4). We propose a race model, similar in some respects to Logan's Independent and Interactive Race model which is used to explain performance in the stop-signal paradigm (Verbruggen & Logan, 2008). Our model proposes competition between an incorrect prepotent response and a correct decision about how or whether to respond. We assume that in general prepotent responses are rapidly but transiently activated by triggering stimuli, whereas correct decisions are reached more slowly through effortful computation. Thus, in the standard versions of the day-night and box-search tasks, the prepotent response is triggered and races to the response threshold before the decision about what to do is made. Imposing a delay after the stimulus is presented gives the prepotent response time to fade (it quickly races to ascendancy, then fades away); children can then compute what to do at their leisure.

If delay is an effective strategy for improving young children's performance, why don't young children use this strategy more often without adult direction? Perhaps they are too impulsive. On the day-night task, young children tend to start out taking their time (and thus responding correctly) but over the course of 16 trials many of them speed up and make errors (Gerstadt *et al.*, 1994). Perhaps their failure to delay is related to a more general difficulty that young children have with implementing strategies. The spontaneous or self-directed use of strategies to improve memory has been studied extensively (see Bjorklund, Dukes & Brown, 2009, for a recent review). The use of memory strategies increases greatly after age 5 (e.g. Coyle & Bjorklund, 1997; DeMarie, Miller, Ferron & Cunningham, 2004; Schneider, Kron-Sperl & Hunnerkopf, 2009). In the delay of gratification paradigm, however, some children as young as age 3 spontaneously use strategies to help themselves withstand a delay (Mischel, Shoda & Rodriguez, 1989). They may steadfastly not look at the tempting treats (even turning around) or occupy themselves with doing, or attending to, something else. Thus, young children *can* use strategies sometimes.

Young children can be taught to use memory strategies by showing children that the strategy can improve their performance (Kreutzer, Leonard & Flavell, 1975) and how to apply it (Schneider & Bjorklund, 1998). Modeling the use of a strategy also helps young children use it (DeMarie-Dreblow & Miller, 1988; Miller, Wood-Ramsey & Aloise, 1991). In a preschool and elementary-school program called PATHS (Promoting Alternative Thinking Strategies), young children are taught the strategy that when they get upset they should stop and take a deep breath (go into their shell like a turtle) and then say what the problem is and how they feel. This has been shown to improve young children's inhibitory control in the classroom (Greenberg, Kusché & Riggs, 2004).

Another example comes from the method used by *Tools of the Mind* (Bodrova & Leong, 2007) educators to 'cure' mirror-reversal writing. Such errors are normal in young children, but often drive teachers to distraction. For example, suppose a child writes '6' reversed, a *Tools of the Mind* teacher simply asks the child, 'When you do your math assignments today, put down your pencil and pick up a red pencil whenever you write the number "6" After that day, the child stops writing 6 reversed. Having to put down one writing implement and pick up another takes time, giving the prepotent tendency to write the 6 reversed time to dissipate. After writing the 6 correctly several times, the tendency to write it reversed is no longer prepotent.

Conclusions

This research investigated how prepotency is modulated – both created and overcome. Diamond and Simpson and Riggs collaborated to test their competing hypotheses.

The responses one plans to make for a game or a task are held in an activated state during that game or task – they become prepotent for that period of time. Therefore, if 'car' is a valid response in the game (i.e. part of the response set for the game) to a stimulus other than a car, if a picture of a car is also a stimulus, then saying 'car' when one sees the picture of a car becomes a pesky, prepotent response that requires effort to inhibit. In contrast, when the name of the picture is never a valid response on the task, the task is easy. In general, of course, children can avoid saying 'car' when they see a car. They have difficulty only when they are primed to say 'car'. Responses become prepotent because of one's intention to produce them.

Children are better able to avoid making prepotent responses when they do not react immediately but pause for a few moments before responding. We explored why that helps. We found that when children do something else during the pause they still succeed in inhibiting the prepotent response. Therefore, they could not be using the pause to compute the correct answer. Something happens independent of their attention and effort. Our model assumes that prepotent responses are rapidly but transiently activated by triggering stimuli. We hypothesize that imposing a delay between stimulus presentation and response gives the incorrect prepotent response time to fade away (it quickly races to the response threshold, then passively dissipates), enabling the correct response to compete more successfully. (The correct response requires effortful computation and so is slower to activate.) Encouraging the use of any strategy that imposes a delay before reacting can help children, and anyone faced with an inhibitory control challenge resist doing something that would get them into trouble or upset others. It gives them time to do what they know they should do, rather than be at the mercy of prepotent tendencies.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Figure S1. *Day-night stimuli used in Experiment 1.*

Figure S2. *Boxes one to eight from the box-search task showing the covering card pulled back to reveal the first box on Trial 1.*

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