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PAPER

Differential effects of reasoning and speed training in children

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Abstract

The goal of this study was to determine whether intensive training can ameliorate cognitive skills in children. Children aged 7 to 9 from low socioeconomic backgrounds participated in one of two cognitive training programs for 60 minutes/day and 2 days/week, for a total of 8 weeks. Both training programs consisted of commercially available computerized and non-computerized games. Reasoning training emphasized planning and relational integration; speed training emphasized rapid visual detection and rapid motor responses. Standard assessments of reasoning ability – the Test of Non-Verbal Intelligence (TONI-3) and cognitive speed (Coding B from WISC IV) – were administered to all children before and after training. Neither group was exposed to these standardized tests during training. Children in the reasoning group improved substantially on TONI (Cohen's d = *1.51), exhibiting an average increase of 10 points in Performance IQ, but did not improve on Coding. By contrast, children in the speed group improved substantially on Coding (*d = *1.15), but did not improve on TONI. Counter to widespread belief, these results indicate that both fluid reasoning and processing speed are modifiable by training.*

Introduction

Fluid reasoning (FR) represents the capacity to think logically and solve problems in novel situations (Cattell, 1987; Horn & Cattell, 1967). Cattell proposed the Investment Hypothesis, whereby FR serves as a scaffold that allows a child to acquire other cognitive skills and knowledge (Cattell, 1987). Indeed, FR is a strong predictor of performance in school, at university, and in cognitively demanding occupations (Floyd, Evans & McGrew, 2003; Fuchs, Fuchs, Compton, Powell, Seethaler, Capizzi, Schatschneider & Fletcher, 2006; Gottfredson, 1997). Although FR is typically thought of as a stable characteristic of an individual, several lines of research have called into question this long-held assumption (Flynn, 2007; Gray & Thompson, 2004; Nisbett, 2009).

Given that FR ability is relevant for scholastic achievement, and that it is likely to be influenced by environmental factors (Flynn, 2007; Nisbett, 2009), we hypothesized that this cognitive skill would be a good target for a cognitive intervention in children from socioeconomically disadvantaged backgrounds. It has been shown that several cognitive skills that support reasoning, including working memory (WM) (Evans & Schamberg, 2009), attention (Mezzacappa, 2004), and language (Noble, McCandliss & Farah, 2007), are compromised by low socioeconomic status (SES), and that academic outcomes are consistently worse for low SES children than for their middle-class peers (Bradley, Convyn, Burchinal, McAdoo & Coll, 2001; McLoyd, 1998).

In the present study, we conducted a cognitive intervention in students of ages 7 to10 at a school with a history of low statewide test scores and a high percentage of economically disadvantaged students. We chose to focus on this age range because the strongest influences of FR on later achievement have been observed among children of ages 5 to 10 (Ferrer & McArdle, 2004; Ferrer, McArdle, Shaywitz, Holahan, Marchione & Shaywitz, 2007).

Over the years, interventions aimed at improving FR have had mixed results (Sternberg, 2008). Several studies have provided evidence that training of working memory, a cognitive function that is strongly related to FR (Engle, Tuholski, Laughlin & Conway, 1999; Fry & Hale, 1996), leads to moderate improvements in FR (Jaeggi, Buschkuehl, Jonides & Perrig, 2008; Klingberg, Fernell, Olesen, Johnson, Gustafsson, Dahlström, Gillberg, Forssberg & Westerberg, 2005; Olesen, Westerberg & Klingberg, 2004; Thorell, Lindqvist, Bergman Nutley, Bohlin & Klingberg, 2009). Further, Holmes and colleagues have shown that training-related gains in WM, even in the absence of corresponding gains in FR, can lead to improvements in academic outcomes (Holmes, Gathercole & Dunning, 2009). On the other hand, Owen

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and colleagues (Owen, Hampshire, Grahn, Stenton, Dajani, Burns, Howard & Ballard, 2010) have found in a large sample of adults that multiple days of playing a set of computerized cognitive tasks online, including FR tasks, does not transfer to a measure of speeded verbal reasoning.

We predicted that a training program targeting children, featuring a variety of computerized and non-computerized reasoning games in a classroom setting, could lead to larger gains in FR than those observed in previous studies. We sought to work with children from low SES backgrounds, since we reasoned that these children would be most likely to benefit from environmental enrichment (Gray, Chabris & Braver, 2003; Raizada & Kishiyama, 2010).

Many prior cognitive intervention studies have included for comparison a group of individuals who did not participate in the training (a passive control group) or a group whose training did not get progressively difficult over time (an active control group with non-adaptive training); other studies simply did not include a control group. Here, we sought to compare the effects of two well-matched training programs that emphasized different cognitive functions – FR and processing speed (PS) – each of which is a critical component of cognition (Gottfredson, 1997; Kail, 1991). Both training programs included a variety of engaging, commercially available games that increased in difficulty as participants improved. Unlike prior studies, in which researchers sought to show a larger improvement in cognitive test scores for the intervention group than the control group upon re-testing, we predicted a double-dissociation in the magnitude of the effects of our two training programs on FR and PS.

Our FR intervention was informed by research on the neural basis and development of this capacity (Ferrer, O'Hare & Bunge, 2009). Many tests of FR require *relational integration*, or the ability to jointly consider distinct relationships between stimuli (Halford, Wilson & Phillips, 1998). Such tests include, but are not limited to, Raven's Progressive Matrices, Tower of London, transitive inference problems, and propositional analogies. Although these tests differ from one another in many ways, they engage common brain regions – lateral prefrontal and posterior parietal cortices – in addition to task-specific regions (Bunge & Wendelken, 2009; Glascher, Rudrauf, Colom, Paul, Tranel, Damasio & Adolphs, 2010; Gray *et al*., 2003; Jung & Haier, 2007). In adults, rostrolateral PFC (rlPFC) plays a specific role in FR: it is primarily engaged on trials that require relational integration (Christoff & Gabrieli, 2002; Christoff, Prabhakaran, Dorfman, Zhao, Kroger, Holyoak & Gabrieli, 2001; Wendelken & Bunge, 2009). Using several of these tests, it has been shown that children aged 7–12 engage the appropriate set of brain regions while performing reasoning tasks, but that they exhibit an immature, non-selective activation profile in rostrolateral prefrontal cortex (Crone, Wendelken, van Leijenhorst, Honomichl, Christoff & Bunge, 2009; Ferrer *et al*., 2009; Wright, Matlen, Baym, Ferrer & Bunge, 2007).

Given the commonalities and differences in brain activation observed across these various FR tasks, we hypothesized that 'cross-training' on various tasks that require relational integration would lead to maximal gains in FR. Importantly, because fluid intelligence characterizes the ability to tackle novel problems, we ensured that children were continually challenged with new tasks.

We designed a speed intervention that emphasized rapid visual detection and rapid motor responses during performance of a variety of games with simple rules. With this training program, we sought to tax PS, or 'the ability to fluently perform cognitive tasks automatically, especially when under pressure to maintain focused attention and concentration' (McGrew & Flanagan, 1998: 24). This skill is considered a central factor in cognitive development. Indeed, Kail and Salthouse (Kail & Salthouse, 1994) have argued that changes in PS over the lifespan underlie many of the observed changes in cognitive performance. Further, Bavelier and colleagues have shown that playing action video games results in improved PS across a variety of perceptual and attentional tasks (for review, see Dye, Green & Bavelier, 2009). We sought to create a speed training program that would include as large a variety of games as the reasoning training program.

PS is thought to contribute to FR only weakly, and indirectly, through its influence on WM (Kail, 2007; Kail & Ferrer, 2007). Thus, while we anticipated that speed training might lead to slight gains in FR, we predicted that gains resulting from direct FR training would be much larger. In contrast, since FR training did not emphasize rapid responding, we predicted that reasoning training would result in minimal or no change in cognitive speed.

In summary, we sought to test whether children who participated in one of two 8-week cognitive training programs would exhibit selective improvements in the targeted cognitive processes. Importantly, both groups participated in active interventions focused on foundational cognitive skills. Given that motivation is critical for learning, we selected commercially available games that were designed to be entertaining. Further, recognizing the importance of social interaction in learning (Gelman, 2009), children in both groups had extensive and equal interactions with the researchers and with other children throughout the program.

Methods

School selection

Our intervention was conducted within an after-school program at an elementary school in Oakland, California. This school was selected based on its low statewide test scores, which place it in the bottom 20% of California schools. Thiry-six percent of students at this school are English language learners. In 2008, over 60% of students failed to achieve proficiency in English, and around 40% failed to achieve proficiency in Math on the California Standards Test. Seventy-two percent of students at this school qualify as economically disadvantaged and receive free or reduced price lunch.

Participants

Children aged 7–10 with no history of neurological or psychiatric illness were recruited from this after-school program with approval from the Institutional Review Board at University of California, Berkeley. Children whose parents spoke languages other than English were included in the study, given the relatively high proportion of these students in the after-school program. However, all potential study participants spoke English fluently. Informed consent was obtained from parents in their native language (Spanish or English), and an information letter was given to children. Participants were randomly assigned to either the reasoning training program or the speed program, which were offered on alternate days of the week (Mondays and Wednesdays or Tuesdays and Thursdays). Data are reported for 17 children (10 boys and seven girls, with a mean age of 8y 6m) who participated in reasoning training, and 11 children (eight boys and three girls, with a mean age of 8y 6m) who participated in speed training. No significant differences were found between groups in demographic measures (see Table 1). Demographic data for individual children can be found in Tables S1 and S2.

The study took place over the course of two semesters, with each child participating in a single 8-week training program. During the first semester, 12 children aged 7–10 participated in reasoning training and 10 children in speed training. The three 10-year-olds in the study (two in the reasoning group and one in the speed group) displayed little interest in playing games with the younger children, and were not fully engaged in the program. As it was evident early in training that the emergent group dynamics were not conducive to learning for the older children, it was decided that the 10-year-olds would be excluded from final data analysis, and that enrollment during the second semester would be restricted to children aged 7–9. Additionally, two children from the speed group were excluded from data analysis based on pre- or post-training assessment scores 2 standard deviations from the means for all children in the study. During the second semester, seven additional children participated in reasoning training and four in speed training. In total, data are presented for 17 children in the reasoning group and 11 children in the speed group. In Tables S1–S5, we provide data for all study participants.

Cognitive assessments

Assessments of cognitive ability were conducted both before and after 8 weeks of training. Standard cognitive measures of PS, FR, and WM were administered by researchers who were not involved in the training program. During the first semester of the training program, assessments were administered in a quiet corner of the training classroom. Since children were assessed on the days they attended training (either Mondays and Wednesdays or Tuesdays and Thursdays), the researchers conducting the assessments during the first semester could deduce each child's training group. During the second semester, assessments were administered in a separate room by a researcher who was blind to the group assignments.

To assess FR, we chose the Test of Nonverbal Intelligence (TONI-3), a matrix reasoning test with two equivalent versions. We administered these versions in a counterbalanced manner between participants, thereby guarding against the possibility that participants would remember the correct answer for a question upon re-testing.

We examined the effects of cognitive training on two different PS measures (Feldmann, Kelly & Diehl, 2004): Cross Out from Woodcock-Johnson-Revised and Coding B from Wechsler Intelligence Scale for Children IV. Cross Out is a timed test in which one must rapidly identify and put a line through each instance of a specific symbol in a row of similar symbols. A row is counted as correct if a child correctly identifies all five instances of the target symbol in that row. The raw score on this assessment is the total number of rows completed correctly in 3 minutes. Unlike Cross Out, Coding requires a mental transformation; it is a timed test in which one must rapidly translate digits into symbols by identifying the corresponding symbol for a digit provided in a legend. The total number of digits translated in 2 minutes serves as the raw score.

Although we did not attempt to train working memory *per se* in either training program, we sought to determine whether playing the reasoning and/or speed games

Table 1 *Demographic information. No significant differences were found in demographic variables between groups*

		Age		Education of primary caregiver		Training days attended		WASI vocabulary raw (normed)	
Training group	Gender	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Reasoning	10 M, 7 F	8.58	0.68	10.33	1.50	12.71	2.37	28.2 (48)	6.66 (9.58)
Speed	8 M, 3F	8.52	0.67	10.50	3.07	12.00	2.05	28.2 (46.2)	8.64 (7.01)

would result in gains in this core cognitive function. We measured working memory with simple span measures of phonological and visuospatial working memory, namely the Digit and Spatial Span tests from the Wechsler Memory Scale. Both span tasks require participants to recall encoded stimuli in the same order in which they were presented (Forward span), and in the reverse order (Backward span). Two trials are presented for each number of stimuli. The raw score represents the number of correct trials. The Forward tests measure the ability to maintain information online, whereas the Backward tests measure the ability to both maintain and manipulate information online. Digit Span and Spatial Span scores are computed as the sum of the Forward and Backward scores for each test.

Training

Each program was offered for 75 minutes per day, 2 days per week for 8 weeks. Sixty minutes of the 75-minute sessions were dedicated to training, and the remaining 15 minutes were used to take attendance, explain games, and provide breaks. Attendance ranged from 8 days to 16 days per child, and mean attendance did not differ significantly between groups (12.7 days for the reasoning group and 12 days for the speed group, $p = .42$). During the first semester, all children began training on the same day. During the second semester, start dates were staggered over the first 3 weeks of training. This modification made it feasible for the researchers performing assessments to be blind to the group assignments.

The games included in the reasoning and speed training programs are listed in Table 3 (for additional information about games and child–researcher interactions, see Data S1). As noted previously, we sought to provide children with a variety of new reasoning games over the course of training. We sought to include a similarly varied set of games in the speed training so that it would be a well-matched control program. Both programs incorporated a mix of commercially available computerized and non-computerized games, as well as a mix of games that were played individually or in small groups. Games selected for reasoning training demanded the joint consideration of several task rules, relations, or steps required to solve a problem. Games selected for speed training involved rapid visual processing and rapid motor responding based on simple task rules.

Each day, children spent 15 minutes at each of four stations: computer games, Nintendo DS games, group non-computerized games, and individual non-computerized games. The remaining time was spent as short breaks between stations. This format kept children on task and engaged for a full hour during each training session. Two researchers managed the non-computerized game stations (one per station), and one researcher managed both computerized game stations. Researchers ensured that children stayed on task and motivated by providing hints and increasing the difficulty of games when appropriate.

Results

Both training programs led to significant improvements in the trained cognitive ability, as measured by standard cognitive assessments. After reasoning training, children were able to solve an average of 4.5 more matrix reasoning problems on the Test of Nonverbal Intelligence (TONI-3) ($t = 4.36$, $df = 16$, $p < .001$; one-tailed p-value reported here and for all subsequent t-tests). This change corresponds to an effect size (Cohen's d) of 1.51 (Figure 1a, Table 2). Before training, children in the reasoning group had an average score of 96.3 points on the TONI, which is normed with a mean of 100 and a standard deviation of 15. After training, they had an average score of 106.2 points. This gain of 9.9 points

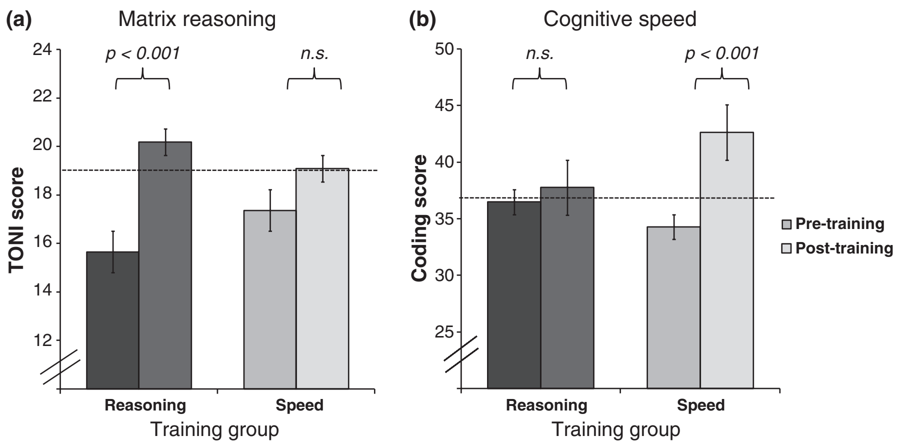

Figure 1 *Raw TONI and coding scores pre- and post- training. Training led to improvement specifically on the trained skill. Dotted lines represent the performance of an average 8.5-year-old child. Error bars represent standard error. Reasoning group: N = 17; Speed group: N = 11.*

Table 2 *Pre- and post-training assessment scores. Significant paired one-tail* t*-tests are bolded. Spatial span was not collected for one subject in the speed group, so post-training data are reported for 10 subjects. Bold* p*-values are significant at* p < .05 *uncorrected. Asterisks indicate* p*-values that survived false discovery rate (FDR) corrected for multiple comparisons (α of .05 adjusted for 14 independent tests:* p < .004*)*

	Reasoning training group (n = 17)						Speed training group (n = 11)					
	Pre-training		Post-training				Pre-training		Post-training			
Assessment	Mean	*SD*	Mean	*SD*	*p*	*d*	Mean	*SD*	Mean	*SD*	*p*	*d*
TONI	15.7	2.6	20.2	3.5	**<.001***	1.51	17.4	4.1	19.1	5.3	.1	0.38
Coding	36.5	4.9	37.8	8.5	.2	0.19	34.3	7.5	42.6	7.8	**<.001***	1.15
Cross Out	14.8	2.7	16.5	3.7	**.002***	0.56	15.4	4.1	18.8	3.5	**<.001***	0.92
Digit Span - Forward	7.4	2.0	7.8	1.8	.19	0.22	7.1	2.4	6.9	2.2	.38	−0.04
Digit Span - Backwards	4.1	1.5	4.5	1.6	.09	0.28	4.1	1.6	5.2	2.1	.08	0.70
Spatial Span - Forward	6.0	1.7	7.1	1.8	**.01**	0.65	7.0	1.7	6.6	1.6	.26	−0.25
Spatial Span - Backwards	4.5	1.9	5.4	2.2	.07	0.41	4.3	2.4	4.5	1.9	.36	0.10

Table 3 *Training games. For computerized and DS games, the company format is as follows: Publisher (Developer). All C games are available for purchase and download at bigfishgames.com. Computerized: C; Non-computerized: NC; Nintendo DS: DS; Indiv.: Individual*

Reasoning games

Game	*Company*	*Format*	*Players*
Set	SET Enterprises	NC	Group
Qwirkle	MindWare	NC	Group
Rush Hour	ThinkFun	NC	Indiv.
Tangoes	REX Games	NC	Indiv.
Chocolate Fix	ThinkFun	NC	Indiv.
Azada	Big Fish Games	C	Indiv.
Azada II	Big Fish Games	C	Indiv.
Big Brain Academy (Think Games)	Nintendo (Edutainment)	DS	Indiv.
Picross	Nintendo (Jupiter Multimedia)	DS	Indiv.
Professor Brainium's Games (Mind Bender)	Nintendo (BOLD games)	DS	Indiv.
Neves	Atlus Co. (Yuke's USA)	DS	Indiv.
Pipe Mania	Empire Interactive (Razorwork Studios)	DS	Indiv.

Speed of processing games

Game	*Company*	*Format*	*Group/Indiv.*
Spoons	n/a	NC	Group
Pictureka	Hasbro Games	NC	Group
Speed	n/a	NC	Group
Blink	Mattel	NC	Group
Perfection	MiltonBradley	NC	Indiv.
Feeding Frenzy	Oberon Media (Sprout Games)	C	Indiv.
Super Cow	Big Fish Games (Nevosoft)	C	Indiv.
Bricks of Atlantis	Arcade Lab	C	Indiv.
Nervous Brickdown	Eidos Interactive (Arkedo Studio)	DS	Indiv.
Super Monkey Ball	Sega	DS	Indiv.
Mario Kart	Nintendo	DS	Indiv.
Ratatouille	THQ (Helixe)	DS	Indiv.

brought the reasoning ability of the group from below average for their age (as indicated by the dotted line in Figure 1a) to just above average. Gains on the TONI were not significant for children in the speed group (1.7 problems; 3.5 points; t = 1.27, df = 10, p = .10).

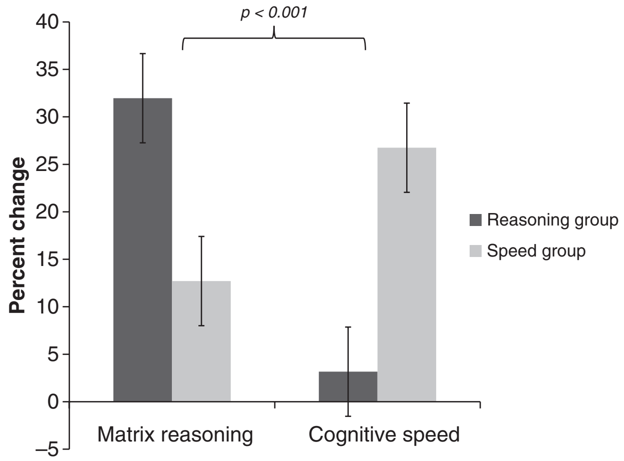

Figure 2 *Double-dissociation in training outcomes. Improvements in the two primary outcome measures show a significant training improvement by training condition interaction. Error bars represent standard error of the ANOVA. Reasoning group:* N = 17*; Speed group:* N = 11*.*

In contrast, children in the speed training group improved significantly on a measure of cognitive speed, Coding (t = 5.35, df = 10, p < .001), whereas children in the reasoning group did not (t = 0.88, df = 16, p = .20) (Figure 1b, Table 3). Children in the speed group were able to complete an average of 8.3 more items on this measure, which corresponds to an effect size of 1.15. Training brought this group from slightly below average for their age (as indicated by the dotted line in Figure 1b) to above average. Both groups improved on Cross Out (Table 3), but the improvement was greater for the speed group (t = 1.76, df = 26, p = .04).

To test for a double-dissociation in training outcomes, we compared the percent change in raw scores on each measure for each group (Figure 2). The training group by outcome interaction was significant (F(1, 26) = 13.03, p < .001), showing that training led to selective improvements in the targeted skill. Reasoning training tended to show larger improvements on the TONI than did speed training (t = 1.63, df = 26, p = .058), and

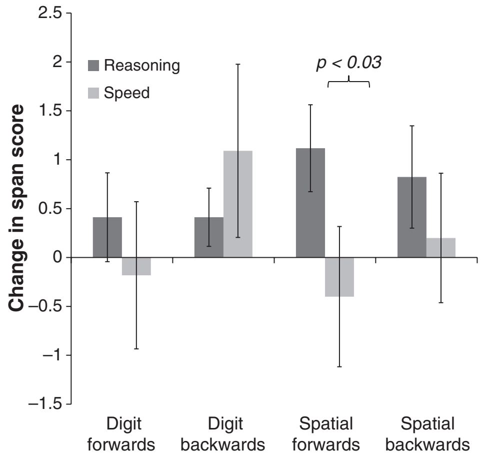

Figure 3 *Improvements in working memory with training. Neither group showed a significant improvement in Forward or Backward Digit Span. The reasoning training group showed a significant improvement in Forward Spatial Span. Error bars represent standard error. Reasoning group:* N *= 17; Speed group:* N *= 11 for Digit Span,* N *= 10 for Spatial Span.*

speed training resulted in larger improvements in Coding than did reasoning training (t = 3.44, df = 26, p = .001).

Several groups have found that intensive practice of a working memory task results in moderate improvements in FR (Jaeggi *et al.*, 2008; Klingberg *et al.*, 2005; Olesen, Macoveanu, Tegner & Klingberg, 2006; Thorell *et al.*, 2009). As such, we sought to test whether children in the reasoning group improved on WM. Because both the FR and PS games required children to keep relevant information in mind, and because they placed an emphasis on visuospatial processing, we hypothesized that children in either or both groups might exhibit gains in WM, particularly on the Spatial Span measure.

Indeed, children in the reasoning group exhibited a moderate improvement on Forward Spatial Span (t = 2.51, df = 16, p = .01; Cohen's d = .65) (Table 2, Figure 3). After training, children in the reasoning group remembered an average of 5.5 locations on the Forward Span task, as compared with 5 locations before training. The reasoning group also showed a trend-level improvement on Backward Spatial Span (t = 1.57, df = 16, p = .07), and therefore the effect of FR training on Total Spatial Span was significant (t = 2.94, df = 16, p = .005). The gain in Total Spatial Span was greater than the gain in the speed group (t = 2.31, df = 26, p = .01), who did not improve significantly on any of the Spatial Span measures. In contrast with the Spatial Span results, neither group exhibited a significant effect of training on Forward or Backward Digit Span. However, there was a trend towards higher Backward Digit Span after PS training (t = 1.54, df = 10, p = .08).

Given that the reasoning group improved on Spatial Span, we sought to determine whether their gains in reasoning could be explained by underlying gains in spatial WM. In fact, our data do not support this hypothesis. Gains on these working memory span measures were not correlated with gains in FR in the reasoning group (Forward Spatial Span: R^2 = .05, p = .37; Backward Spatial Span: R^2 = .06, p = .36), or in both groups combined (Forward Spatial Span: R^2 = .02, p = .46; Backward Spatial Span: R^2 = .11, p = .09). In other words, participants who improved the most on TONI were not necessarily the same individuals who improved substantially on the spatial working memory span task. It is an open question whether reasoning training would have resulted in improvements on more demanding measures of working memory, such as the complex span tasks of Engle and colleagues (Engle *et al.*, 1999).

Next, we sought to test whether initial FR and PS scores and/or days of training predicted training outcomes. We found a significant negative correlation between pre-training TONI scores and TONI improvement (R^2 = .33, p = .02). We did not find a correlation between pre-training Coding and Coding improvement (R^2 = .09, p = .37). In summary, children who began the intervention with the lowest FR scores showed the largest gains in FR after reasoning training. Initial PS scores did not predict gains in PS after speed training. Gains were also not correlated with training days attended – either when each group was considered separately (FR: R^2 = .02, p = .62; PS: R^2 = .08, p = .71), or when percent change in the targeted skill was considered for both groups (R^2 = .01, p = .69).

Discussion

We found that a mere 8 weeks of playing commercially available games can lead to large improvements on standard cognitive tests of FR and PS in children. To our knowledge, this study provides the first clear evidence of a double-dissociation in cognitive gains between two training programs in children, and the strongest effect of training on FR. Both programs targeted general cognitive skills that are central to cognitive development (Fry & Hale, 1996; Kail, 2007) and that have the potential for widespread influences.

Particularly surprising is the finding that FR training resulted in an average gain in Performance IQ of almost 10 points, with four of the 17 children showing gains of over 20 points. This large effect underscores the point that FR is modifiable by environmental influences, contrary to claims that it is a relatively fixed ability (Cattell, 1987). Indeed, the very existence and widespread use of IQ tests rests on the assumption that tests of FR measure an individual's innate capacity to learn. These and other findings (Diamond, Barnett, Thomas & Munro, 2007; Jaeggi *et al.*, 2008; Klingberg *et al.*, 2005; Rueda, Rothbart, McCandliss, Saccomanno & Posner, 2005) indicate that cognitive training *can* influence FR, even if it does not always do so (Owen *et al.*, 2010). This collective evidence suggests that prior experience does impact test performance – even on FR tests, which were designed to be 'culture fair' (Cattell, 1987).

In addition to the large effect on FR, reasoning training also had a moderate effect on Spatial Span (Cohen's d = .65). Calculated in the same way, Klingberg and colleagues' spatial WM training research has yielded effect sizes on Spatial Span ranging from .86 in children with ADHD (Klingberg *et al.*, 2005) to .89 in preschool children (Thorell *et al.*, 2009). The absolute amount of improvement in our study (2 points in Spatial Span) was similar to that found by Klingberg and colleagues. Thus, our results indicate that just as engaging in progressively more challenging spatial working memory problems results in improved spatial WM, so too does playing a variety of engaging reasoning games that rely on visuospatial processing.

Our results may appear to contradict recent findings by Owen and colleagues (Owen *et al.*, 2010), who have shown that computerized training games targeting FR and WM do not transfer to gains on other tasks. However, several factors make it difficult to compare results across studies, including differences in the study populations (children from low SES backgrounds vs. typical adults), training settings (a classroom setting vs. unsupervised training at home), and outcome measures (a standard visuospatial reasoning test vs. a speeded verbal reasoning test).

Speed training led to roughly a 30% improvement on Coding. To our knowledge, this is the first study that has found large training gains in PS in children. While these gains did not transfer to gains in WM, as one might predict based on Fry and Hale's Developmental Cascade Model (Fry & Hale, 1996), the trend observed for Digit Span Backwards suggests that a significant effect might emerge with a larger sample size – and/or with complex span measures of WM (Conway, Kane & Engle, 2003). Additionally, the speed group showed a trend towards improvement on the TONI. However, this gain is difficult to interpret without a passive control group, as we cannot determine whether this gain is larger than would be expected from test–retest effects.

Potential caveats and future directions

Although our findings are very encouraging, some issues deserve attention. Due to the intensive nature of our training programs, our sample size was fairly small. With a larger sample size, it would be possible to assess the influence of each of the following factors on training outcomes: training-related variables (e.g. days attended, semester of enrollment), demographic variables (age, gender, socioeconomic status), and cognitive functioning prior to training.

In addition, because we administered assessments in an after-school setting, we had limited time to assess each child. Therefore, we had to choose tests of PS, WM and FR that could be administered quickly, and we were not able to administer as many tests of each skill as would have been ideal. It is unclear whether reasoning or speed training would have transferred to gains on complex span measures of WM, like those designed by Engle and colleagues (Conway *et al.*, 2003).

We chose not to compare gains to a passive control group (i.e. a group of children who took only pre- and post- assessments) because we wanted every child who signed up to be assigned to an active training program. We were concerned that the children whose parents would sign them up for this option could be different from the other two groups in ways that are difficult to quantify (e.g. parental involvement and attitudes towards research and/or educational opportunities). Without a passive control group, we were limited in our ability to interpret the trend towards improvement on the TONI in the speed group, and the gain on Cross Out in the speed group.

Training in a social environment has many benefits, but it does not lend itself to tight experimental control over instruction and task progression. It was not possible to standardize feedback from researchers and from other children. We have matched the two training programs in terms of researcher interactions to the best of our ability, but there is no question that training programs aimed at different cognitive skills would involve different teaching strategies. Further, we do not have the data to address the question of which games (e.g. computerized vs. non-computerized, or group vs. individual) had the greatest impact on cognitive skills. We hypothesize that no single game drove the effects that we observed, but instead that the variety of games helped to train FR and PS from multiple angles, while sustaining the children's interest.

Further research is needed to determine how FR and PS training influence brain structure and/or function. We hypothesize that FR training would lead to repeated co-activation of parietal and lateral prefrontal regions that support the processing and integration of visuospatial relations. This repeated co-activation could, in turn, lead to activity-dependent changes in these regions, such as myelination and dendritic branching. Ongoing and future studies incorporating neuroimaging methods could provide further insight into these potential mechanisms for training-related gains in cognitive skills.

Additional research is also needed to address the following critical questions. How long do these training effects last? Even if training effects fade without continued practice, the finding that these skills are malleable is important. Gains in physical fitness would not be expected to be maintained without practice, but this does not mean that exercise is not beneficial. Can training-related gains in cognitive skills lead to improved academic outcomes? The encouraging results of these and other recent cognitive training studies warrant the pursuit of larger-scale research that includes academic outcome measures.

The central message of this paper is hopeful. Even though there is increasing evidence that cognitive skills are compromised in low SES children (Kishiyama, Boyce, Jimenez, Perry & Knight, 2009; Noble *et al.*, 2007; Stevens, Lauinger & Neville, 2009), there is also increasing evidence that cognitive skills are amenable to training (Raizada & Kishiyama, 2010). Notably, our work and others' shows that cognitive training need not be expensive. Simple instructional strategies and inexpensive commercially available games can be used to train core cognitive processes in children who stand to benefit most.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Training Information

Table S1 Demographic information for the reasoning training group

Table S2 Demographic information for the speed training group

Table S3 Reasoning and speed raw scores for the reasoning training group

Table S4 Reasoning and speed raw scores for the speed training group

Table S5 Working memory scores

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