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Distraction during relational reasoning: The role of prefrontal cortex in interference control

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Abstract

We compared the reasoning performance of patients with frontal-variant frontotemporal lobar degeneration (FTLD) with that of patients with temporal-variant FTLD and healthy controls. In a picture analogy task with a multiple-choice answer format, frontal-variant FTLD patients performed less accurately than temporal-variant FTLD patients, who in turn performed worse than healthy controls, when semantic and perceptual distractors were present among the answer choices. When the distractor answer choices were eliminated, frontal-variant patients showed relatively greater improvement in performance. Similar patient groups were tested with a relational-pattern reasoning task that included manipulations of one or two relations and both perceptual and semantic extraneous information. Frontal-variant patients showed performance deficits on all tasks relative to the other subject groups, especially when distracted. These results demonstrate that intact prefrontal cortex (PFC) is necessary for controlling interference from perceptual and semantic distractors in order to reason from relational structure.

Keywords: Reasoning; Distraction; Interference; Relational; Control; Attention

1. Introduction

Reasoning requires the coordinated activity of several brain regions. The subprocesses of reasoning include manipulation of information in working memory, formation of transient connections between individual problem elements, and inhibition of inappropriate responses. These cognitive processes are thought to be governed largely by the prefrontal cortex (PFC) (D'Esposito et al., 1995; Fuster, 2000; Smith & Jonides, 1999; Wallis, Anderson, & Miller, 2001).

Patients with frontotemporal lobar degeneration (FTLD) have a form of dementia that causes atrophy to cortical regions within the frontal and temporal lobes (Knibb, Kipps, & Hodges, 2006; Rosen et al., 2002; Snowden, Neary, & Mann, 2007). Onset of cortical atrophy may begin in either the frontal or anterior temporal regions and progress to include both areas, but instances can be found in which cortical damage is restricted to either the frontal or temporal lobes (Chow, Miller, Boone, Mishkin, & Cummings, 2002). In such cases it is possible to dissociate the patient groups based on behavioral and cognitive symptoms and neuroimaging. Frontal and temporal variants of FTLD provide models that can assist us in better characterizing the contributions of the PFC to reasoning performance, and specifically to examine the role of the PFC in control of interference from distracting information during relational reasoning.

Prior studies indicate that frontal-variant FTLD (fvFTLD) leads to reasoning deficits that can be characterized as failures in manipulating and integrating multiple relations in order to solve problems (Waltz et al., 1999). In addition, deficits in interference control also contribute to relational reasoning

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impairments in fvFTLD patients (Morrison et al., 2004). Interference control is an important aspect of relational reasoning (see Morrison, Doumas, & Richland, 2006; Morrison et al., 2004; Richland, Morrison, & Holyoak, 2006; Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004), as it is necessary to avoid compelling semantic or perceptual matches that compete with matching based on relational structure (Gentner & Toupin, 1986; Holyoak & Koh, 1987; Krawczyk, Holyoak, & Hummel, 2004, 2005; Markman, 1997). While the PFC has historically been considered to be important for inhibitory processes that may underlie interference control (Butter, 1969; Iverson & Mishkin, 1970; Miller & Cohen, 2001; Quintana, Fuster, & Yajeya, 1989; Shimamura, 2000), this function has had relatively little direct investigation in the domain of reasoning. The current investigation specifically tests the extent to which interference control is important for visual reasoning tasks in which suppressing semantically and perceptually related items is essential for accurate performance.

Studies of the neural underpinnings of relational reasoning initially focused on the PFC and its contribution to the ability to coordinate attention and working memory (Holyoak & Kroger, 1995; Robin & Holyoak, 1995). Several of these studies were based on the framework advanced by Halford (e.g. Halford, Wilson, & Phillips, 1998), which quantifies relational complexity of information as the number of variables that must be integrated in order to solve a problem. The relational complexity metric has been applied to reasoning studies in development (e.g. Andrews & Halford, 2002; Birney, Halford, & Andrews, 2006; Richland et al., 2006), aging (Viskontas, Holyoak, & Knowlton, 2006), and chromosomal disorders (Fales et al., 2003).

This approach is exemplified by studies in which PFC-damaged subjects were compared to other subject groups that lacked frontal impairments. Waltz et al. (1999) tested fvFTLD patients on a version of the Raven's progressive matrices (RPM; Raven, 1941), and a transitive inference task. The RPM has been considered to encapsulate many of the skills that comprise fluid intelligence (Duncan et al., 2000; Snow, Kyllonen, & Marshalek, 1984). Notably, this task requires the ability to maintain different pieces of relational information (about changes in different dimensions) and integrate them to form a solution. Findings showed that frontal-damaged groups failed selectively on problem types that required the integration of multiple relations, compared to those problems in which only one relation was required for a correct solution. Similar findings were obtained with frontally impaired Alzheimer's disease patients on matrices problems and relational working memory problems (Waltz et al., 2004).

Recent studies (Morrison et al., 2006; Viskontas et al., 2004) have suggested that developmental and patient differences in relational reasoning as characterized by relational complexity can best be accounted for by variation in inhibitory control, a suggestion consistent with the importance of PFC in relationally complex reasoning. The involvement of the PFC in analogical and relational reasoning studies has received further support from neuroimaging studies. Early studies investigated the neural correlates of variations of the RPM. Prabhakaran, Smith, Desmond, Glover, and Gabrieli (1997) found predominantly PFC and parietal lobe activation in an fMRI study of this task. Similar results have been reported by Christoff et al. (2001) and Kroger et al. (2002), both of whom reported anterior rostrolateral PFC regions to be selectively active for the most complex matrix problems that required integrating across several dimensions. Relational processing has also been shown to activate PFC in neuroimaging studies of geometric and mathematical reasoning (Melrose, Poulin, & Stern, 2007; Prabhakaran, Rypma, & Gabrieli, 2001).

Recent functional neuroimaging studies of analogical reasoning have revealed evidence of further PFC specialization. Across several studies, investigators have reported left-anterior PFC activation that appears to be selective for the relational mapping aspect of analogical reasoning (Bunge, Wendelken, Badre, & Wagner, 2005; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; Luo et al., 2003). In one study, Bunge et al. (2005) found both left-anterior and ventrolateral PFC areas to be associated with processing analogies; however, the ventrolateral PFC alone was also sensitive to word association strength, suggesting that this region was more involved in semantic retrieval than relational integration. The other studies also found broad PFC activation in response to processing analogy problems, but the anterior portion of the PFC has been found to be most sensitive specifically to the relational demands of the tasks. This pattern of findings indicates that relational reasoning appears to selectively recruit rostrolateral PFC, but that the process overall involves more of the PFC as well as relevant posterior regions (Wharton et al., 2000). This movement toward separation of function of PFC areas in complex reasoning is consistent with recent theoretical claims that the PFC can be divided into subprocessing regions linked by an anterior control system (Christoff & Owen, 2006; Koechlin, Ody, & Kouneiher, 2003; Koechlin & Summerfield, 2007).

A second important feature of many tasks that are sensitive to frontal impairments is the need to control interference from extraneous information. For example, in the Wisconsin Card Sorting Test the tendency to respond based on a consistent dimension must be suppressed in order to shift response dimensions at the appropriate time. Similar impairments have been shown in both the human and animal literature with reversal learning deficits following PFC damage, in which responses to a previously rewarded stimulus must be suppressed in order to respond correctly to a previously unrewarded stimulus (Butter, 1969; Iverson & Mishkin, 1970; O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001; Rolls, Hornak, Wade, & McGrath, 1994). In a prior study we demonstrated that frontal-variant FTLD patients show a specific deficit in solving two-choice A:B::C:D style verbal analogy problems when a semantic distractor item, closer in association to the C term than the correct D term, was presented as a possible answer choice (Morrison et al., 2004). Furthermore, we showed in a picture analogy task that fvFTLD patients tended to provide many perceptually similar answers, rather than analogical answers, compared to healthy control subjects. This aspect of analogical reasoning has received relatively little direct investigation in PFC-impaired patients.

The current study seeks to more precisely characterize fvFTLD deficits in relational reasoning problems that involve the need to suppress semantic and perceptual distractors. In the study of Morrison et al. (2004), we demonstrated that fvFTLD patients show deficits in verbal analogy performance due to close semantic distractor items, and independently demonstrated that they tended to match to perceptually similar items over relational items in a separate picture analogy task. A limitation of the latter task was that it utilized a free-choice procedure, in which participants looked for what they considered to be the generally best match, but were not specifically required to try to find relational analogy matches. Thus, it was not clear if patients were actually impaired in suppressing distracting information, or if this information was simply very salient to the patients. Because we did not include both semantic and perceptual distractors in the same analogy task, we were unable to determine whether semantic or perceptual sources of distraction introduce greater task difficulty for patients with frontal lobe impairments. In Experiment 1 we addressed these issues by directly testing frontal- and temporal-variant FTLD (tvFTLD) patients on an explicit analogy task requiring subject to try to make relational matches, while simultaneously including both perceptual and semantic distractors as answer choices. Further, we re-tested several of the subjects at a later time with a version of the task that eliminated semantic or perceptual distractors in order to determine whether fvFTLD patients would show an increase in the ability to give relational answers when sources of distraction were removed.

As noted earlier, prior reasoning tasks have focused on the integration of multiple relations as a critical aspect of task performance that requires intact PFC (Waltz et al., 1999, 2004). Several attempts have been made to study the interaction of relational complexity and distraction in development (Morrison et al., 2006; Richland et al., 2006; Viskontas et al., 2004) and in healthy young adults (Cho, Holyoak, & Cannon, 2007); however, possible interactions have yet to be systematically studied in patient populations. In Experiment 2 we present data from a relational-pattern task that requires subjects to detect relational changes in one or two dimensions and integrate these changes to answer the problems. The problems are similar to the Raven's matrices task, but are somewhat simpler and involve only one or two levels of relational complexity. In addition to the relational complexity manipulation, we added semantic and perceptual information extraneous to the problems in order to test the hypothesis that fvFTLD patients will show a deficit on problems involving distracting information, and to test whether this deficit specifically interacts with relational complexity level.

While this paper focuses on assessing the reasoning performance of fvFTLD patients, we also consider the impact of tvFTLD on reasoning performance. We hypothesize that tvFTLD patients will show some impairment on picture analogies due to their loss of semantic knowledge. They are less likely to show impairments based on distraction and overall we predicted that their performance on both tasks would be superior to that of fvFTLD patients.

2. Methods (Experiment 1)

2.1. Participants

The characteristics of all participants are summarized in Table 1. Patients were recruited on the basis of neurological diagnoses of FTLD following the guidelines of Neary et al. (1998). The classification of patients as frontal or temporal variant was made using imaging data and cognitive and behavioral symptoms (SPECT, PET, or structural MRI). MMSE scores were above 20 for all participants. This experiment received approval from the Institutional Review Boards of UCLA, UCSF, and USC and has therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All participants provided informed consent to participate. There were no significant differences in age or education among any of the participant groups. A subset of the participants were tested at their homes and paid $10 for their participation, while others were tested at a clinic as part of a battery of cognitive testing. Two problem sets were used in Experiment

Table 1
Participant characteristics for Experiment 1: picture analogies

Measure	fvFTLD patients				tvFTLD patients				Healthy controls			
	Distractor set		No-distractor set		Distractor set		No-distractor set		Distractor set		No-distractor set	
	n	*M*	*n*	*M*	*n*	*M*	*n*	*M*	*n*	*M*	*n*	*M*
Characterizing												
Age	10	61.00	5	57.00	6	60.00	4	60.00	10	64.00	8	61.00
Education	10	15.10	5	16.40	6	17.75	4	17.25	10	16.95	8	17.19
MMSE	10	25.90	5	25.40	6	26.17	4	25.75	–	–	–	–
Executive												
WCST	7	36.00	3	32.00	1	14.00	1	14.00	–	–	–	–
Stroop A	6	62.50	1	77.00	1	36.00	0	–	–	–	–	–
Stroop B	5	71.60	0	–	1	29.00	0	–	–	–	–	–
Stroop C	5	108.25	0	–	1	88.00	0	–	–	–	–	–
Working memory												
Digit Fwd	8	7.25	3	8.67	3	6.67	3	6.67	–	–	–	–
Digit Bkwd	7	4.43	2	4.50	3	5.67	3	5.67	–	–	–	–
Semantic memory												
BNT (60 items)	7	74.43%	2	78.5%	1	83.00%	1	97.00%	–	–	–	–

1, the distractor set and the no-distractor set. The distractor set was completed by 10 fvFTLD patients, 6 tvFTLD patients, and 10 healthy control participants. The no-distractor set was completed by 5 of the 10 fvFTLD patients, 4 of the 6 tvFTLD patients, and 8 of the 10 healthy control subjects. This difference in participant numbers between the two problem sets was due to the fact that we had initially begun testing the patients with the distractor set before developing the no-distractor set for comparisons in performance.

2.2. Materials

Picture analogy problems were presented in the format A:B::C:D, where the D item was absent and needed to be completed with one of four answer choices presented beneath the problem (see Fig. 1A). The A and B items (e.g. sandwich and lunchbox) were presented to the left of a vertical line. The C item (hammer) and a question mark were presented to the right of this line. There were four answer choices presented below the problem in all instances. Two versions of the problem set were presented, the distractor set and the no-distractor set. A subset of the analogy problems were modified versions of problems from the Goranson Analogy Test (Goranson, 2002).

The distractor set consisted of 16 problems. Answer choices included the correct analogical answer (the toolbox in Fig. 1A), a semantically related distractor item that came from the same semantic category as the C item of the analogy (the nail), a perceptually related distractor that looked similar to the C item (the gavel), and an unrelated distractor item that had no strong relationship to the C item (the ribbon). The specific ordering of answer choices was randomized throughout the problem set and the order of presentation was randomized across all participants. The serial position of the answer choices was counterbalanced such that each answer type appeared an equal number of times in each of the answer choice positions throughout the problem set. Refer to Appendix A for a complete list of the items used in the problems.

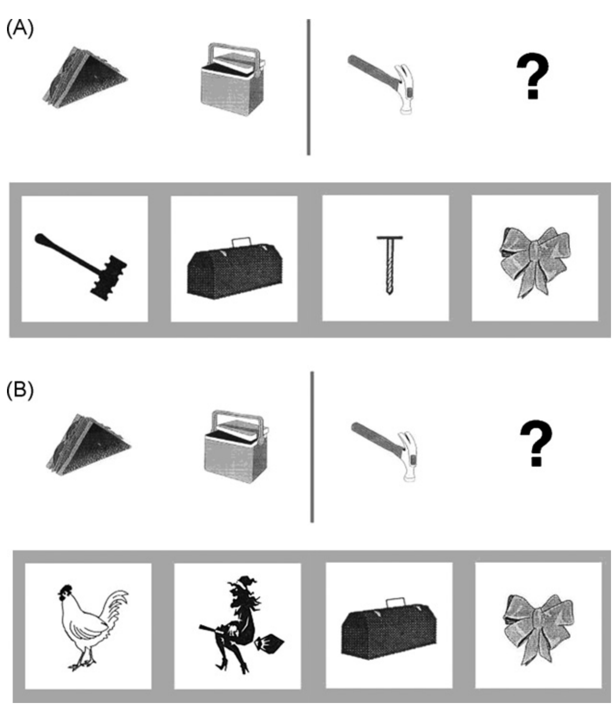

Fig. 1. A sample problem from the picture analogy set. (A) Analogy item from the distractor set—sandwich:lunchbox::hammer:? in which the answer choices are the correct analogical answer (toolbox), an unrelated item (ribbon), a perceptual distractor (gavel), and a semantic distractor (nail). (B) Representation of the same problem from the no-distractor set. Note that three unrelated answer choices have replaced the three incorrect answer choices shown in (A).

The no-distractor set was identical to the first set with two exceptions: the correct answer appeared in a different spatially ordered position among the answer choices than it had in the distractor set, and the semantic and perceptual incorrect answer choices used in the distractor set were replaced with items unrelated to the C term of the problem (the chicken and witch in Fig. 1B). The no-distractor set was also presented in a new randomized order across all participants. The correct analogical answer appeared an equal number of times in each of the answer choice positions. Refer to Appendix B for a complete list of the items used in the no-distractor problems.

2.3. Procedure

Participants were initially tested on the distractor set. All instructions and problems were presented on a laptop computer positioned at a comfortable distance from the participant. The experimenter read a series of instructions stating that the participant should think about the relationship between the first two pictures to the left of the vertical line, and consider what would go with the third picture to the right of the vertical line to complete a similar relationship. Participants were instructed that they would first see each problem and should consider what they thought the relationship between the items to the left of the vertical line was, and that after a brief amount of time (2 s) the answer choices would appear beneath the problem. Two example problems were included during the instruction period. After each practice problem the experimenter explained which answer was correct and clarified the inter-item relationships that made it the correct answer. Following the instructions, participants completed the distractor set. The experimenter pointed to each picture item presented in each problem and named it in order to clarify what each picture represented. Participants chose their answer by pointing to the choice on the screen or saying their answer choice aloud. The experimenter entered the key corresponding to the chosen answer.

The No-Distraction condition followed a delay of 30–45 min during which the participant completed an unrelated cognitive task. The same instructions were presented to the participants in the no-distractor set condition as they had received for the distractor set condition. The example problems were the same, but included three unrelated incorrect choices along with the correct analogical answer (refer to Fig. 1B). Following the instructions, participants completed the no-distractor set using the same procedure that had been used in the distractor set condition.

2.4. Statistics

Differences in accuracy between the different patient groups on the distractor problem set were evaluated using analyses of variance with Bonferroni-corrected post hoc tests to determine whether specific differences were robust. Additional ANOVAs were carried out to test whether other answer choices were significantly different among the groups. Performance on the no-distractor set was compared to that on the distractor set using a repeated-measures ANOVA, while specific within-group comparisons were made using Bonferroni-corrected post hoc tests.

3. Results (Experiment 1)

3.1. Distractor set

Fig. 2 shows the mean percentages of different answer choices made by each of the participant groups. The number of correct analogical answers was initially compared among the three participant groups using a one-way ANOVA, which revealed a significant difference among the three groups, $F(2, 23) = 17.91$, $p < .001$. Bonferroni-corrected post hoc tests ($p < .05$) showed that normal controls provided a significantly greater percentage of correct answers than both fvFTLD patients and tvFTLD patients. In addition, tvFTLD patients provided more correct answers than fvFTLD patients. These findings establish that both patient groups showed lowered performance

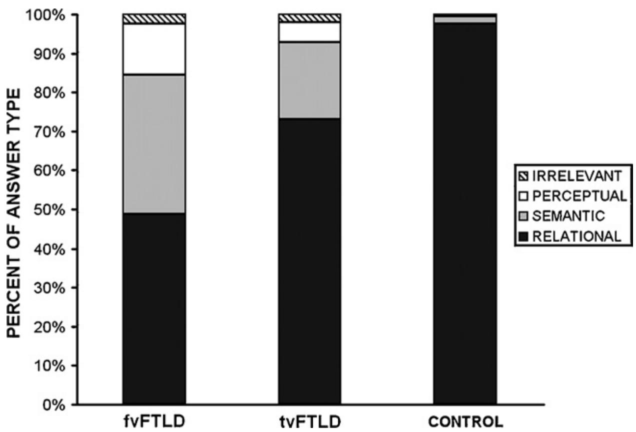

Fig. 2. Results of the distractor set in the picture analogy task. fvFTLD patients reported fewer correct answers compared to tvFTLD patients and healthy controls. tvFTLD patients also showed decreased correct responding relative to healthy controls. Furthermore, only fvFTLD patients failed to report more correct matches than semantic distractor matches.

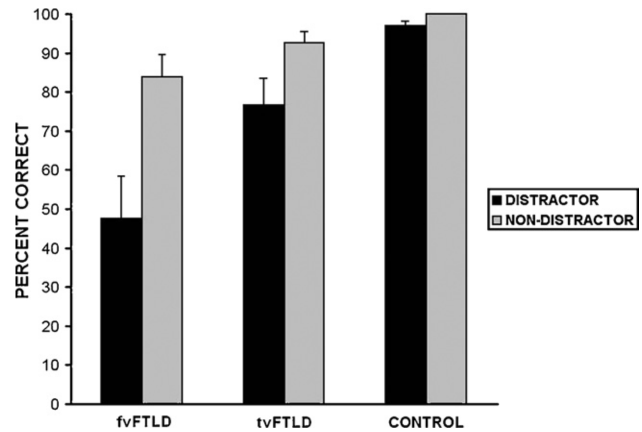

Fig. 3. Mean improvement in correct analogical answers from the distractor set to the no-distractor set in the picture analogy task. Only fvFTLD patients showed a reliable improvement between the two sets with distractors removed. Error bars denote standard error of the mean.

on the analogy task, with fvFTLD patients showing the greatest impairment.

We conducted similar analyses on the other answer categories (semantic distractor, perceptual distractor, and unrelated item). In these analyses we found a significant difference among the participant groups for number of semantic distractors, $F(2, 23) = 11.57$, $p < .001$, with Bonferroni post hoc tests ($p < .05$) revealing that fvFTLD patients made more semantic distractor choices than healthy controls. No other differences were significant for the semantic distractor items. A significant difference was also found for perceptual distractor items, $F(2, 25) = 3.41$, $p = .05$, with Bonferroni post hoc tests revealing that fvFTLD patients made more perceptual distractor choices than healthy controls. There were no significant differences among unrelated answer choices among any of the participant groups. These results indicate that fvFTLD patients were especially prone to making errors that involved choosing either the semantic or perceptual distractor item relative to control subjects. In addition, temporal-variant patients tended to select distractor items at a greater level than normal controls, perhaps due to semantic deficits.

To further test our hypothesis that fvFTLD patients would be particularly susceptible to making errors based on semantic relatedness, we conducted dependent-samples *t*-tests comparing the numbers of semantic errors to correct analogical answers within each subject group. These analyses revealed that fvFTLD patients showed no significant difference between the percentage of correct analogical answers ($M = 49\%$) and incorrect semantic distractor answers ($M = 36\%$), $t(9) = 0.90$, $p = .39$. These differences were significant for tvFTLD patients (analogical $M = 73\%$, semantic $M = 20\%$), $t(5) = 5.29$, $p < .01$, and for healthy control participants (analogical $M = 98\%$, semantic $M = 2\%$), $t(9) = 51.00$, $p < .001$. This pattern of results supports the hypothesis that control of semantic interference is a cognitive function supported by the PFC, as only the frontal-variant patients failed to provide reliably more analogically correct answers than semantic distractor answers.

3.2. No-distractor set

The number of analogically correct answers was compared among the three subject groups using a 3 (group) × 2 (test session) repeated-measures ANOVA. This analysis revealed a significant main effect of test, $F(1, 14) = 50.59$, $p < .001$ and a significant task by group interaction, $F(2, 14) = 16.11$, $p < .001$. Bonferroni-corrected post hoc tests ($p < .05$) revealed that normal controls provided significantly more correct answers ($M = 100\%$) than frontal-variant FTLD patients ($M = 84\%$). No other comparisons were significant. These data are summarized in Fig. 3.

We further analyzed the degree of improvement between tests for the three subject groups using Bonferroni-corrected dependent-samples *t*-tests ($p < .05$). These analyses revealed a significant improvement for fvFTLD patients, who gave a greater number of analogical answers on the no-distractor set compared to the distractor set, $t(4) = 5.03$, $p < .01$. There were no reliable differences in improvement for the other participant groups. This result indicates that fvFTLD patients disproportionately benefited from the absence of distraction from perceptually and particularly semantically related answers in the no-distractor set. This finding is consistent with the hypothesis that a source of performance failure in reasoning in fvFTLD patients is the inability to suppress related but incorrect answers.

4. Methods (Experiment 2)

4.1. Participants

The characteristics of the 17 participants are summarized in Table 2. Three of the fvFTLD patients and two of the tvFTLD patients had also participated in Experiment 1. Patients with FTLD were recruited on the basis of neurological diagnosis following the guidelines of Neary et al. (1998). The extent of damage to either the frontal or temporal cortex was determined using imaging data (SPECT, PET, or structural MRI). Mini-mental Status Exam scores were above 20 for all participants. This experiment received approval from the Institutional Review Boards of UCLA, UCSF, and USC and has therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All participants provided informed consent to participate. There were no significant differences in age or education among any of the participant

Table 2
Participant characteristics for Experiment 2: relational-pattern reasoning task

Measure	fvFTLD patients		tvFTLD patients		Healthy controls	
	n	*M*	*n*	*M*	*n*	*M*
Characterizing						
Age	9	58.89	4	61.50	6	59.00
Education	9	16.50	4	18.13	6	17.75
MMSE	9	26.22	4	25.50	6	–
Executive						
WCST	2	43.00	1	9.00	–	–
Stroop A	2	69.50	0	–	–	–
Stroop B	0	–	0	–	–	–
Working memory						
Digit Fwd	6	6.83	3	6.00	–	–
Digit Bkwd	7	3.75	2	5.50	–	–
Semantic memory						
BNT (60 items)	2	78.5%	1	100%	–	–

groups. Frontal-variant participants were first screened to determine whether they could reliably solve one-relation/no distraction problems in the practice phase prior to the task. Participants were either tested at their home and paid $10 for their participation, or in a clinic environment as part of a cognitive testing battery.

4.2. Materials

A set of 80 relational-pattern reasoning problems was presented in this task. Each problem followed the same format, showing three cartoon pictures of a person with arrows indicating that the cartoons should be viewed from left to right (see Fig. 4). There were four versions of cartoon people that appeared in equal numbers in the problem set. Each problem featured one version of a cartoon person exclusively. Two male and two female cartoon people were used in the problems. The males wore red and blue clothes, respectively, and the females wore green or magenta clothes. Clothing color was fixed for each cartoon character. The variations of clothing color and gender of the cartoon people were included to make the task less-reliant upon perceptual features only, and to discourage perseverative responding based on specific features of the stimuli in the patient groups.

Problems were constructed to include one-relation and two-relation problems. One-relation problems showed either a size change, in which the cartoon person started small and became progressively larger in the next two images (see Fig. 4A), or showed a color change in which the cartoon person's outfit started in a light shade and became progressively darker shades of the same color in the next two images (see Fig. 4A). Two-relation problems showed both size and color shade changes in the same three cartoon images (see Fig. 4A). The problems were counterbalanced so that each of the four cartoon people was included in 25% of the problems within each relational and distraction category.

Participants had to judge whether a complete relation change occurred for all relations present in each problem. For example, a "true" one-relation size problem showed the cartoon person starting small and becoming larger

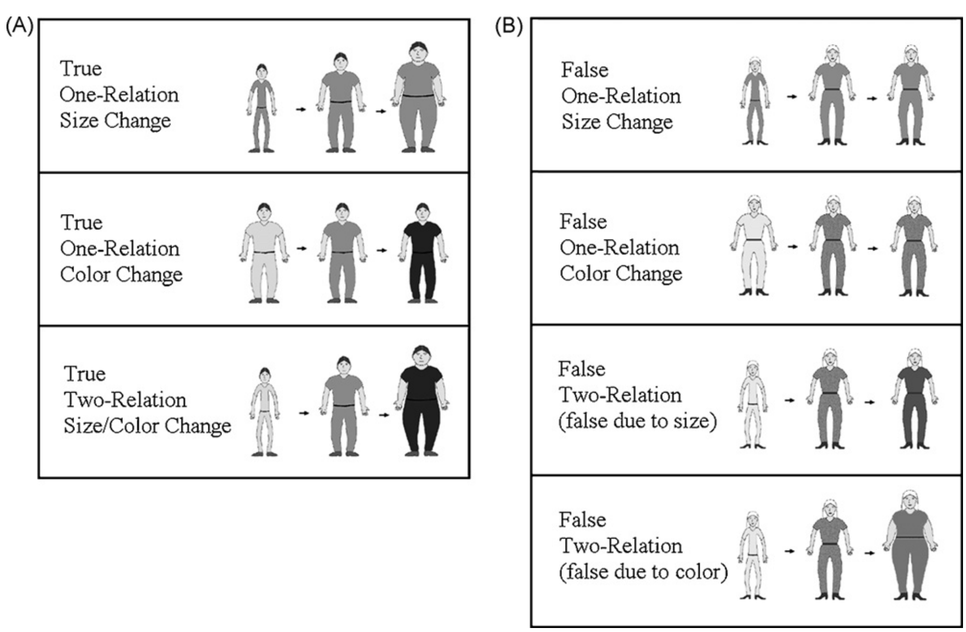

Fig. 4. Examples of the relational-pattern reasoning problems. (A) Representations of different types of "true" problems from the task showing a one-relation size change, a one-relation color change, and a two-relation change in which both size and color change. (B) Representations of different "false" problems showing instances in which person 1 and 2 change, but person 3 does not.

in each image (see Fig. 4A), or starting with light shade clothes and becoming darker in each image. A "false" one-relation problem showed a change occurring from the first cartoon image to the second, but no change occurring from the second cartoon to the third (see Fig. 4B). For "true" two-relation problems both relations showed complete patterns (both size and color shade would change progressively from the first to the third cartoon image). In a "false" two-relation problem, the cartoon person showed a complete pattern for one relation (e.g. size), but an incomplete pattern for the other (e.g. color shade; refer to Fig. 4B). Problems were counterbalanced so that size and color shade represented the false relation an equal number of times in the one-relation and two-relation problems. In addition, the problem set included 40 relationally true problems and 40 relationally false ones; these appeared in equal proportions for one-relation and two-relation problems.

4.3. Semantic-Distraction

In addition to relational change, several subsets of the problems included distracting clothing or accessories added to the three cartoon people. These accessories were included in order to provide a relatively familiar source of distraction from the correct relational answer to the problems. One semantic-distraction (S-D) problem subset consisted of 32 problems to which two theme-related accessories were added to each cartoon person in the problem. For example, there was a firefighter theme that showed the first character with a fire hose and coat, the second with a fire hat and axe, and the third with a fire extinguisher and boots. Refer to Appendix C for a list of the theme-related items that were added to the cartoon people. In addition to the firefighter theme there was a western theme, a fishing theme, and a baseball theme.

An additional 32 S-D problems were constructed by including theme-related clothing in each of the three people in a given problem. For example, one such problem included the western theme clothing in which each cartoon person wore a separate version of the western clothing (see Appendix C). It should be noted that in this case the western theme unifies the three people; however, the specific clothing items were never repeated in these problems to avoid additional perceptual similarity. A subset of 16 of the S-D problems was theme consistent meaning that a particular theme clothing set appeared for each of the three cartoon people (e.g. all fishing-themed, see Fig. 5A). The remaining 16 S-D problems were theme-inconsistent, meaning the theme-related clothing accessories for the first two cartoon people were from the same category (e.g. all fishing-themed), but the clothing theme was different for the third cartoon person (e.g. firefighter-themed, see Fig. 5A). This manipulation enabled us to include problems in which the theme-related accessories would aid participants in solving them (relationally true/theme-consistent and relationally false/theme-inconsistent problems), as well as problems in which the theme-related accessories would hinder participants (relationally true/theme-inconsistent and relationally false/theme-consistent problems). The S-D problems were counterbalanced so that an equal number of relationally true and relationally false problems appeared with theme-consistent and theme-inconsistent accessories.

4.4. Perceptual-Distraction

Thirty-two perceptually distracting (P-D) items were included in the problem set. In these cases three identical sets of accessories were included for each cartoon person in the problem. For instance all three cartoon people may have had a cowboy hat and a lasso. These problems were either perceptually consistent, with all three people wearing identical accessories (see Fig. 5B), or perceptually inconsistent, with one person wearing a different set of items from the same theme (e.g. person 1 and person 2 wore a baseball hat and held a baseball, while person 3 wore a baseball shirt and held a baseball bat; see Fig. 5B). As with the S-D problems, the use of consistent and inconsistent distractor accessories allowed us to construct 16 perceptually consistent problems in which the distractor items could potentially help participants to solve the problems (relationally true/perceptually consistent and relationally false/perceptually inconsistent), as well as 16 perceptually inconsistent problems that potentially led participants away from the correct answer (relationally true/perceptually inconsistent and relationally false/perceptually consistent problems). The P-D problems were counterbalanced so that an equal number of relationally true and relationally false problems appeared with perceptually consistent and perceptually inconsistent accessories.

4.5. Procedure

Participants were initially told that they would see three pictures of a person that should be viewed from left to right on the screen and that they should look for all of the ways that the person changes. The experimenter then showed examples of the one-relation change problems and described the manner in which each change occurred. The experimenter further explained that both color and size may change in one problem and an example of this type was shown. Participants were then told that they should respond "true" if all changes were complete in the problem. Examples of true one-relation problems in which size or color changed were shown. An example of a true two-relation problem was also shown. Participants were next told that they should respond "false" to any problem in which any of the changes were not complete. Examples of one-relation color and size problems were then shown, as was an example of a false two-relation problem. The experimenter fully explained the types of changes and why each one was either true or false, as well as pointing out the visual characteristics that should be attended to.

At this time the participant completed a practice phase consisting of 10 problems. Included in this practice phase were examples of each type of problem that would be encountered in the actual test, including both one-relation and two-relation problems, each type of true and false problem, each type of one-relation change, and each of the four cartoon people. After this phase, participants were shown example problems with the S-D and P-D accessories and were told to ignore the accessories when they appeared and to answer the problems based on the instructions given previously. Participants then completed a second practice phase consisting of 10 representative problems based on answer type and number of relational changes present. Half of the problems in this set were S-D and half were P-D. The experimenter answered participant questions about the problems

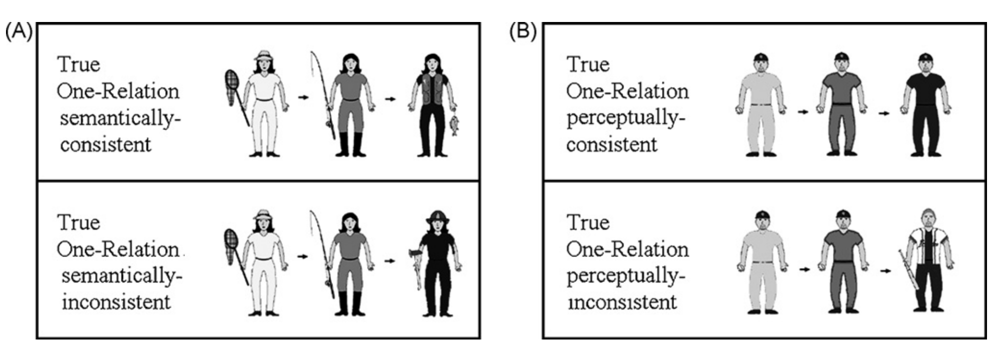

Fig. 5. Examples of the types of distracting information included in the relational-pattern reasoning problems. Semantically distracting information included all people having extraneous clothing from the same class of items (e.g. fishing gear), or from different classes of items (e.g. fishing gear and fire-fighting gear). Perceptually distracting information involved all people wearing identical outfits (e.g. baseball caps and gloves), or all people wearing semantically related outfits, but one of the three having perceptually different accessories than the others.

and explained each answer during the practice phases. The full 80 problem set was then completed.

5. Results (Experiment 2)

We tested for differences in performance among the different subject groups and levels of relational complexity using an analysis of variance with Bonferroni-corrected post hoc tests. This was followed up with specific tests of the frontal patient performance using the *d*' statistic, which is sensitive to detecting response criteria based on signal detection theory (Wickens, 2001). A repeated-measures ANOVA was carried out to test whether frontal patients performed differently on problems varying in distraction and in relational complexity.

Fig. 6A shows the mean proportion correct for the one-relation and two-relation problems for each group with and without distraction present. The proportion of correct one-relation and two-relation problems was analyzed using a 2 (relation-level) × 3 (distraction-type) × 3 (participant group) mixed ANOVA. This analysis revealed a significant difference among the three groups, $F(2, 16) = 17.51$, $p < .001$. Bonferroni-corrected post hoc tests ($p < .05$) revealed that a greater percentage of correct answers were provided by normal controls ($M = 99\%$) and tvFTLD patients ($M = 99\%$) than fvFTLD patients ($M = 68\%$). There were no other significant differences found in this initial analysis.

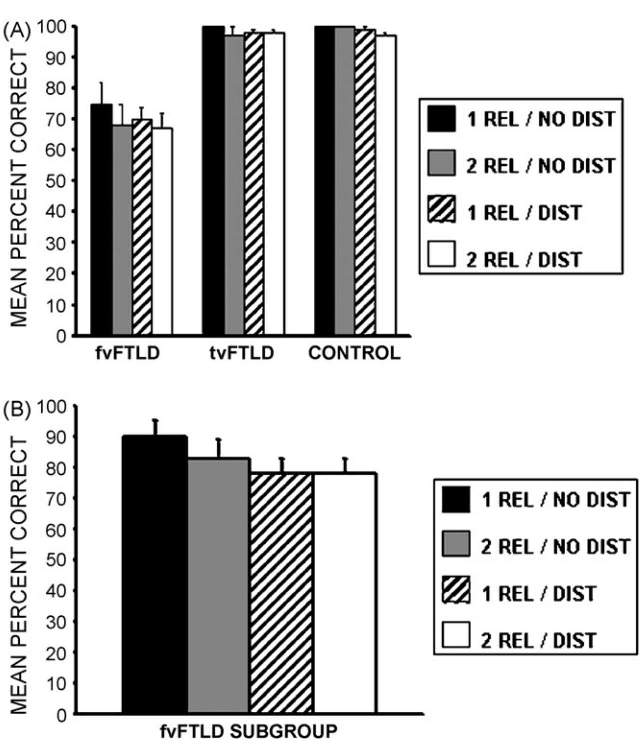

Fig. 6. Performance on the relational-pattern reasoning task. (A) Overall, fvFTLD patients provided fewer relationally correct answers than the other groups. Furthermore, this group showed a selective deficit for distraction problems over non-distraction problems. (B) Data from the fvFTLD patients who were non-perseverative. This group showed evidence of distraction being a key factor in the performance impairment of this group. Error bars denote standard error of the mean.

Some subjects in the fvFTLD group showed a tendency to perseverate in the way they responded during the task, relying predominantly on only the true or the false response across the majority of problems. In order to account for this performance difficulty, we computed *d*' measures based on signal detection theory (Wickens, 2001) in order to assess the extent to which subjects were sensitive to balancing hit rates with false alarm rates. This analysis revealed that a subset of four subjects in this group had been indiscriminant in their responses as computed by *d*'. We eliminated those four subjects who failed to achieve a *d*' measure above 0.50 from subsequent analyses. This choice of threshold eliminated only those subjects who had shown strong evidence of perseveration.

The data from the subgroup of fvFTLD subjects that survived the *d*' elimination were tested using a 2 (distraction) × 2 (relation) repeated-measures ANOVA. This planned-comparison resulted in a main effect of distraction $F(1, 4) = 17.75$, $p < .05$, such that these subjects solved significantly more no-distractor problems ($M = .86$) than distractor problems ($M = .78$). There was no reliable effect of relational complexity, though these means were numerically different in the predicted direction (one-relation $M = .81$, two-relation $M = .73$). There was no significant interaction between distraction and relational complexity level. These data indicate that distraction is an important factor influencing the errors made by this subject group.

6. Discussion

These results illustrate the importance of the PFC for intact reasoning performance on tasks that require relational processing in the presence of competing perceptual and semantic information, suggesting that control of interference may be a critical factor necessary for properly appreciating the relational structure relevant to reasoning.

In Experiment 1, we demonstrated that both groups of FTLD patients were impaired on picture analogy performance relative to healthy controls. This finding is similar to our prior results with verbal analogy materials (Morrison et al., 2004). In that paper, we applied a neurally plausible computational model of analogy (LISA; Hummel & Holyoak, 1997, 2003, 2005) to support the hypothesis that fvFTLD patient's analogy deficits may stem largely from inhibitory control problems. This position is consistent with our current picture analogy results (Experiment 1), where fvFTLD patients performed worse than temporal-variant patients and healthy controls on the problems containing semantically or perceptually attractive distractor items (distractor set). Importantly, when these distractor items were removed and replaced with less attractive alternatives (no-distractor set), fvFTLD patients improved more than temporal-variant patients. The finding suggests that fvFTLD patients may have been able to solve the analogies reasonably well in the absence of distractor choices and that the presence of particularly semantic distractors may be sufficient to disrupt analogical reasoning when the inhibitory control functions of PFC are operating sub-optimally.

A potential alternative interpretation is that performance improved in the no-distractor condition because participants were not actually attempting to solve the analogy task, but rather just selecting the answer choice most semantically related to the C term of the analogy. However, if this strategy had been employed we would have expected fvFTLD performance to be near ceiling in the no-distractor condition, where the correct answer (i.e., the D term) was almost always the most semantically related term among the choices present. In fact, fvFTLD patients made a substantial number of errors even when no semantic distractors were present among the choices, suggesting that these patients were not simply selecting the most associated term. Although this pattern of results weakens the plausibility of this alternative interpretation, it still may be the case that fvFTLD patients rely on semantic association more than controls in analogy tasks due to poor relational processing.

The presence of perceptual distractors in the distractor version also appears to have contributed to deficient performance in fvFTLD patients but to a lesser degree than the semantic distractors as greater proportions of semantic errors were obtained in Experiment 1. Perceptual distractors have been shown to decrease responding based on relational information in frontal-variant patients in our previous study with scene analogies (Morrison et al., 2004).

The tvFTLD patients performed better than fvFTLD patients but worse than healthy controls in the picture analogy tasks. This deficit in tvFTLD subjects on the distractor set in Experiment 1 appears to be related to the semantic concept loss commonly seen in these patients. This group does not generally show specific deficits in interference control (Neary, Snowden, Northen, & Goulding, 1988); rather, their performance deficit in the distractor set may have been due to loss of specific relational category information necessary to solve the analogies. While we did not specifically vary the association strength of various answer choices, inspection of the choices (see Appendix A) suggests that the semantic distractors may on the whole be more associated to their respective C terms than were the correct relational terms. Importantly, the tvFTLD group did not benefit from the no-distractor set to the degree that the fvFTLD patients did. Presumably the temporal-variant patients had lost the relational category linking the C and D terms, and thus lacked the necessary information to solve the analogy regardless of presence of a distractor. This finding is also consistent with the hypothesis that interference control is principally dependent on PFC and not anterior temporal cortex.

The results of Experiment 1 are consistent with the hypothesis that suppressing compelling semantic or perceptual, but relationally incorrect, mappings is a core cognitive skill necessary for correct analogical reasoning. Current computational models of analogy have considered inhibitory control to be an important mechanism (Hummel & Holyoak, 1997, 2003, 2005), but few prior studies have directly tested the extent to which deficits in interference control are responsible for failures of analogical reasoning. Our results, along with our previous work (Morrison et al., 2004), support the hypothesis that inhibitory control is critical for analogical reasoning and that it is linked to the PFC.

In Experiment 2 we tested the extent to which relational reasoning can be disrupted by relational complexity and by inhibition of extraneous information in PFC-damaged patients. The results of this study show a clear performance deficit for fvFTLD patients over tvFTLD patients and controls. Analysis of the fvFTLD group performance indicated that these patients had the greatest difficulty on problems that required control of interference from irrelevant extraneous information. This finding demonstrates strong support for a frontal deficit in control of interference during reasoning. All subjects had received prior training on how to solve the problems relationally and had been explicitly and repeatedly told to ignore all of the extraneous information by the experimenter. The fact that fvFTLD patients could not ignore the extra information is particularly striking under these conditions. In Experiment 1, the distractors represented an alternative answer choice that had to be considered to select the correct relational choice; however, in Experiment 2 the relevant relations necessary for solving the problems had nothing to do with the extraneous perceptual and semantic distractors and yet these features still interfered with fvFTLD patient performance. fvFTLD patients were reminded by the experimenter that they were to focus on the relevant color and size relations only and to ignore the additional clothing distraction prior to the actual task, yet they still exhibited sporadic difficulties due to these factors.

The deficit in interference control for fvFTLD patients in Experiment 2 was observed for both semantic and perceptual forms of distraction. We had designed the task to allow for subjects to inappropriately solve the problems based on alternative strategies related to the distractor clothing. For example, subjects could have answered “true” for problems in which the extra clothing worn by the characters made them perceptually or semantically similar or dissimilar. The results failed to support the use of such strategies, but rather indicated that fvFTLD patients tended to perform at lower levels when any distraction was present in the problems. It is also important to note that these patients did not perform at ceiling levels for non-distractor problems, suggesting that their deficit involves additional processes besides distraction from the extraneous features.

Contrary to our predictions, we did not observe a significant effect of relational complexity on fvFTLD patient performance in Experiment 2, although performance on higher relational complexity problems was relatively worse in the fvFTLD group than in the other groups. The integration of two or more relations in solving matrix problems has previously been argued to be a frontally mediated process (Christoff et al., 2001; Kroger et al., 2002; Prabhakaran et al., 1997; Waltz et al., 1999, 2004). The low number of non-perseverant subjects in Experiment 2 may have limited the statistical power to find a significant relational complexity difference. Another factor that may have contributed to the lack of a clear complexity difference is that the relations of size and color were potentially decomposable in this task. Decomposable relations can be considered independently and thus processed serially. By this interpretation, correct two-relation performance requires intact maintenance of independent relational solutions, but not necessarily relational integration. The lack of completely non-decomposable relations may have worked against finding a strong relational complexity effect. It should also be noted that the fvFTLD group was somewhat impaired relative to controls in the one-relation, no distraction problems. This difference may be an indication that relational processing deficits are a core feature of the frontal-damaged profile, which may have been exacerbated by the presence of distraction.

It is also interesting to note that while tvFTLD patient performance was compromised in Experiment 1, which required use of previously learned category information, these patients were more successful in Experiment 2, which required participants to learn and use several new categories. This result is consistent with recent category learning results with FTLD patients (Koenig, Smith, & Grossman, 2006), which suggests that the PFC is more important than anterior temporal cortex for learning new categories, whereas anterior temporal cortex is critical for the long-term storage of category information.

The results of these two experiments converge to demonstrate that intact PFC is necessary for effective relational reasoning. These results, as well as those reported previously (Morrison et al., 2004), indicate that distracting semantic associates, whether presented verbally or visually, tend to interfere with the ability of fvFTLD patients to select the correct relational choice for an analogy. These data extend the findings from neuroimaging studies of frontal involvement in relational reasoning (Bunge et al., 2005; Christoff et al., 2001; Green et al., 2006; Kroger et al., 2002; Luo et al., 2003; Wharton et al., 2000), indicating that a core function of the PFC is to avoid distraction and maintain a goal-directed focus on forming the correct relational answer.

Recent models of working memory suggest close interconnections between inhibition and the binding of concepts in working memory. Oberauer (2005) has argued that binding of concepts in working memory can explain results that appear to stem from deficits in inhibitory control. This position fundamentally assumes that difficulties in working memory arise from the limited capacity to bind together information. This position is broadly consistent with our working memory model based on LISA (Hummel & Holyoak, 1997, 2003), which proved capable of simulating verbal analogy performance under high distraction conditions (Morrison et al., 2004). In this simulation, the joint factors of reduced learning rate and impaired ability to filter alternative items resulted in successful simulation of the fvFTLD deficit in that analogy task. Thus variations in these two factors can jointly lead to impairment of dynamic binding in working memory. Data from the current study do not definitively demonstrate whether the fvFTLD deficit stems from a binding problem, or more purely an inhibitory problem (Hasher & Zacks, 1988). These two positions are not incompatible, but rather may both constitute cognitive effects of frontal impairment, as we have argued in connection with working memory changes during cognitive development (Morrison et al., 2006) and aging (Viskontas et al., 2004).

Our results demonstrate how two core PFC functions, interference control and relational integration in working memory, are related to specific forms of problem solving. While the function of the frontal lobes has been widely considered to include various forms of cognitive control (Aron, 2007; Butter, 1969; Iverson & Mishkin, 1970; Rubia, Smith, Brammer, & Taylor, 2003), the present results show that interference can disrupt the reasoning process in cases in which distractors are present, even when distracting information is completely unrelated to the rules that define the problem. Theories of relational reasoning should thus include interference control as a central cognitive operation required for successful problem solving.

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Appendix A

Analogy problem	Correct answer	Perceptual distractor	Semantic distractor	Unrelated answer
Practice set				
Gas pump:car, candy bar:?	Boy	Book	Mint candy	Tree
Squirrel:tree, fish:?	Glass bowl	Rocket	Hook	Camera
Distractor set				
Radio:ear, television:?	Eyes	Spaceship	TV remote	Ship
Fork:salad, glass:?	Milk carton	Trash can	Baby bottle	Dice
House:tree, igloo:?	Ice	Tea kettle	Eskimo	Maid
Toothbrush/paste:teeth, soap:?	Hands	Book	Hand towels	Sofa
Sling:arm, cane:?	Leg	Candy cane	Walker	Ladder
Rake:gardener, scissors:?	Seamstress	Pliers	Tape	Clown
Lamp:light bulb, candle:?	Fire	Rocket	Flashlight	Envelope
Dentist:drill, doctor:?	Stethoscope	Conductor	Medical logo	Bananas
Baseball:baseball player, football:?	Football player	Lemon	Soccer ball	Scale
Airplane:bird, boat:?	Fish	Factory	Locomotive	Boot
Grapes:wine, pumpkin:?	Pie	Basketball	Witch	Books
Plant:gardener with water, boy:?	Woman w/food	Robot	Toys	Scale
Typewriter:page sewing machine:?	Dress	Electric mixer	Needle & thread	Bread
Shirt/tie:luggage, paper:?	Briefcase	Towel	Pencil	Electric plug
Sandwich:lunchbox, hammer:?	Toolbox	Gavel	Nail	Ribbon
Cheese:cow, fried egg:?	Chicken	Amoeba	Bacon	Violin

Appendix B

Analogy problem	Correct answer	Unrelated answer	Unrelated answer	Unrelated answer
Practice set				
Gas pump:car, candy bar:?	Boy	Baseball	Dice	Trashcan
Squirrel:tree, fish:?	Glass bowl	Needle/thread	Book	Bread
No-distractor set				
Radio:ear, television:?	Eyes	Pencil	Ring	Envelope
Fork:salad, glass:?	Milk carton	Rocket	Tree	Hook
House:tree, igloo:?	Ice	Nail	Toolbox	Gas pump
Toothbrush/paste:teeth, soap:?	Hands	Train	Rocket	Bacon
Sling:arm, cane:?	Leg	Bacon	Ladder	Amoeba
Rake:gardener, scissors:?	Seamstress	Cow	Violin	Mixer
Lamp:light bulb, candle:?	Fire	Teeth	Tape	Pliers
Dentist:drill, doctor:?	Stethoscope	Book	Towel	Electric plug
Baseball:baseball player, football:?	Football player	Sandwich	Lamp	Pliers
Airplane:bird, boat:?	Fish	Boot	Toys	Eskimo
Grapes:wine, pumpkin:?	Pie	Books	Car	Tree
Plant:gardener with water boy:?	Woman w/food	Factory	Locomotive	Scale
Typewriter:page, sewing machine:?	Dress	Mint candy	Camera	Fish
Shirt/tie:luggage, paper:?	Briefcase	Light bulb	Robot	Nail
Sandwich:lunchbox, hammer:?	Toolbox	Chicken	Witch	Ribbon
Cheese:cow, fried egg:?	Chicken	Tree	Walker	Violin

Appendix C

Theme/version	Accessory 1	Accessory 2
Baseball A	Baseball cap	Baseball
Baseball B	Baseball glove	Cleats
Baseball C	Baseball shirt	Baseball bat
Firefighter A	Coat	Fire hose
Firefighter B	Firefighter hat	Axe
Firefighter C	Fire extinguisher	Boots
Fishing A	Net	Fishing hat
Fishing B	Fishing vest	Fish on line
Fishing C	Fishing pole	Wading boots
Western A	Cowboy hat	Lasso
Western B	Sheriff vest	Cowboy boots
Western C	Holsters	Bolo tie

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