Involvement of the Inferior Frontal Junction in Cognitive Control: Meta-Analyses of Switching and Stroop Studies

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Introduction

The inferior frontal junction (IFJ) is a brain region located at the junction of the inferior frontal sulcus and the inferior precentral sulcus. In a number of functional imaging studies (for review, see Brass et al., 2005), we have found evidence for the involvement of the IFJ in cognitive control processes. In particular, we have shown that the IFJ was commonly activated in a within-subject study employing the Stroop task, a task-switching paradigm, and a verbal n-back task (Derrfuss et al., 2004). Here, we investigate the consistency of IFJ involvement in color-word Stroop and switching paradigms by employing a quantitative meta-analytic approach.

Methods

Procedure

- Search of Medline/PubMed and ISI Web of Science; and search of references of studies found in those databases
- Only frontal lobe and insula activations included
- Coordinates reported in MNI space were transformed to Talairach space

Inclusion criteria

- Switching studies: studies employing task-switching, set-shifting, and non-probabilistic S-R reversal paradigms
- Stroop studies: studies employing variants of the color-word Stroop task
- Studies published in English-language, peer-reviewed journals between January 2000 and January 2004
- Only fMRI studies reporting coordinates in stereotaxic space and covering at least the frontal lobes; only studies with healthy participants
- Only subtraction designs, but no null-event or resting baseline contrasts and no multiple subtractions from the same condition of interest; no ROI analyses

Studies included

- Switching studies: 14 studies with 97 activation maxima entered the switching meta-analysis (Table 1)
- Stroop studies: 11 studies with 64 activation maxima entered the Stroop meta-analysis (Table 2)

Data processing

- Activation likelihood estimate (ALE) maps as described by Turkeltaub et al. (2002) were created using a FWHM of 9.4 mm
- These ALE maps were thresholded at $\alpha < 0.01\%$ (the corresponding ALE threshold was derived from random distributions of activation maxima)

REFERENCES:

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Turkeltaub, P. E., Eden, G. F., Jones, K. M., & Zeffiro, T. A. (2002). Meta-analysis of the functional neuroanatomy of single-word reading: method and validation. *Neuroimage, 16*(3 Pt 1), 765-780.

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Table 1
Task-switching, set-shifting, and S-R reversal studies included in the meta-analysis.

Author	Year	Design	Partic.	Task/Contrast	Activ.	IFJ
Brass	2004	efMRI	14	TS, meaning-switch vs. cue-switch	2	-37 5 32
Braver	2003	e/bfMRI	13	TS, switch vs. repeat (event-related analysis)	3	-
DiGirolamo[1]	2001	bfMRI	8[2]	TS, switch blocks vs. repeat blocks	13	(-46 12 34)
Dove	2000	efMRI	16	S-R reversal, switch vs. repeat	5	-44 5 37
						40 8 36
Dreher	2002	bfMRI	8	TS, switch/rep. blocks (conjunction of switch conditions) vs. pure blocks	4*	-
Konishi	2002	efMRI	16	WCST variant, update vs. null change	3*	-38 4 33
Kringelbach	2003	efMRI	9	S-R reversal, reversal vs. no reversal	5	-
Luks	2002	efMRI	11	TS, informative switch cue vs. baseline	10[4]	-
Luks	2002	efMRI	11	TS, neutrally cued switch vs. baseline	3[4]	-
Monchi	2001	efMRI	11	WCST variant, negative FB vs. control FB	12*	-38 3 27
						-46 5 27
Monchi	2004	efMRI	9[3]	WCST variant, negative FB vs. control FB	9*	-44 9 33
						44 9 33
Nagahama	2001	efMRI	6	WCST variant, negat. FB vs. sorting baseline	7*	46 7 29
Nagahama	2001	efMRI	6	S-R reversal, negative FB vs. sorting baseline	6*	(-42 3 26)
Nakahara	2002	efMRI	10	WCST variant, neg. FB vs. sorting baseline	10*[5]	34 4 35
Pollmann	2000	efMRI	12	S-R reversal, switch vs. repeat	4	45 2 37
Swainson	2003	efMRI	12	TS, go switch vs. go repeat	1*	-

Note. [1] as this study used an unusually low threshold of $z > 1.96$ (with no correction for multiple comparisons or application of a cluster threshold) and in comparison to other studies reported a very high number of activations (30), we decided to include only activations above a more conservative threshold of $z > 3.09$; [2] young participants; [3] control group; [4] some of these activations were located within ROIs, but each activation was significant on a whole brain level at $p < 0.001$ (Tracy Luks, pers. comm.); [5] coordinates published in Online Supplementary Material; Abbr.: efMRI = event-related fMRI, e/b = mixed design, bfMRI = blocked fMRI; TS = task switching, WCST = Wisconsin Card Sorting Test, FB = feedback; Activ. = number of frontal lobe activations, * = transformed from MNI to Talairach space; IFJ = activations within IFJ limits, () = activations close to IFJ

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Table 2
Stroop studies included in the meta-analysis.

Author	Year	Design	Partic.	Task/Contrast	Activ.	IFJ
Banich	2000	bfMRI	10	Stroop word monitoring, I/N vs. N	4	(-48 10 34)
Banich	2001	bfMRI	14	CW Stroop, I/N vs. N	3	-42 10 34
Fan	2003	efMRI	12	CW Stroop, I vs. C	4*	-
Mead	2002	bfMRI	18	CW Stroop, I vs. N	1	-44 4 29
Milham	2001	e/bfMRI	16	CW Stroop, I vs. N (event-related)	4	-42 2 36
Milham	2002	bfMRI	12[1]	CW Stroop, I vs. C/N	8	(-46 14 32)
Milham	2003	efMRI	16	CW Stroop, I vs. oddball neutral	9	-
Norris	2002	SE bfMRI	7	CW matching Stroop, I vs. N	6	-38 4 33
Potenza	2003	efMRI	11[2]	CW Stroop, I vs. C	6	43 7 35
Steel	2001	bfMRI	7	CW Stroop, I vs. N	14	-
Zysset	2001	bfMRI	9	CW matching Stroop, I vs. N	5	-38 5 30

Note. [1] young participants; [2] control group
Abbr.: efMRI = event-related fMRI, bfMRI = blocked fMRI, SE = spin echo, e/b = mixed design; CW = color-word, I = incongruent, C = congruent, N = neutral; Activ. = number of frontal lobe activations, * = transformed from MNI to Talairach space; IFJ = activations within IFJ limits, () = activations close to IFJ

Results

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Table 3
Meta-analysis of frontal lobe and anterior insula activations in task-switching, set-shifting, and non-probabilistic S-R reversal studies.

Region	~ BA	Lat.	x	y	z	ALE	mm^3
Inferior frontal junction	6/8/44	L	-40	4	30	0.024	3032
Inferior frontal gyrus	44/45	L	-48	14	18	0.021	s.c.
Inferior frontal junction	6/8/44	R	44	10	34	0.022	1700
Inferior frontal sulcus	46/45	R	46	28	24	0.017	268
ACC/pre-SMA	32/6	B	4	8	48	0.028	2659
Superior frontal gyrus (med.)	8	B	4	28	42	0.020	s.c.
ACC/SFG (med.)	32/8	B	-8	20	42	0.016	s.c.
Insula		R	32	22	2	0.018	215

Note. Clusters above an ALE threshold of 0.0133 ($p < 0.0001$) and a minumum size of 10 mm^3 are listed; minimum peak distance is 5 mm. Coordinates are in Talairach space.

Abbr.: ACC = anterior cingulate cortex, pre-SMA = pre-supplementary motor area, med. = medial, SFG = superior frontal gyrus, ~ BA = approximate Brodmann's area, Lat. = lateralization, B = bilateral, ALE = activation likelihood estimate, s.c. = same cluster

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Table 4
Meta-analysis of frontal lobe and anterior insula activations in color-word Stroop studies.

Region	~ BA	Lat.	x	y	z	ALE	mm^3
Inferior frontal junction	6/8/44	L	-40	4	32	0.022	1250
ACC/pre-SMA	32/6	B	2	14	42	0.019	797
ACC/SFG (med.)	32/9	L	-2	36	26	0.015	199
Insula		L	-26	22	6	0.014	133
		R	36	12	6	0.013	74

Note. Clusters above an ALE threshold of 0.0116 ($p < 0.0001$) and a minumum size of 10 mm^3 are listed; minimum peak distance is 5 mm. Coordinates are in Talairach space.

Abbr.: ACC = anterior cingulate cortex, pre-SMA = pre-supplementary motor area, SFG = superior frontal gyrus, med. = medial, ~ BA = approximate Brodmann's area, Lat. = lateralization, B = bilateral, ALE = activation likelihood estimate

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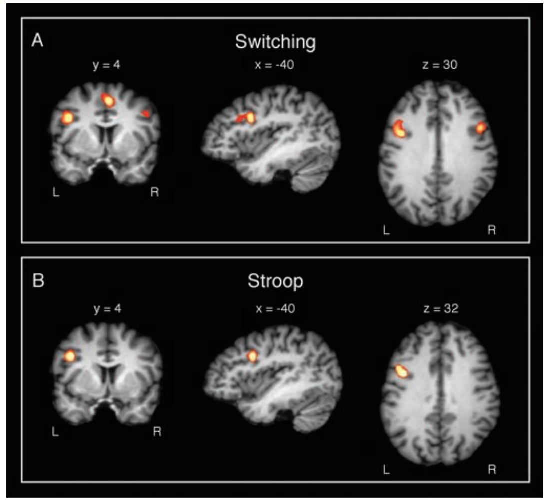

Figure 1:
Results of the quantitative meta-analyses. Displayed are above-threshold voxels at the IFJ peak coordinates for (A) switching and (B) Stroop studies. Results are shown on an individual brain in Talairach space and were interpolated to mm-resolution for display purposes. Note that only frontal coordinates entered the meta-analyses.

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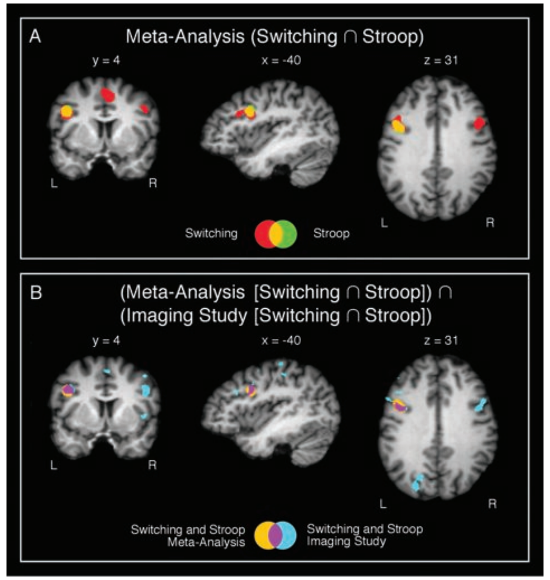

Figure 2:
A) Overlap analysis at the IFJ for switch and Stroop meta-analyses.
B) Overlap analysis for the meta-analytic results and the results from a functional imaging study. From the imaging study, the overlap from the switch vs. null event contrast and from the Stroop incongruent vs. neutral contrast is shown (these results - with the additional inclusion of an n-back task - are reported in detail in Derrfuss et al., 2004).
Results are shown on an individual brain in Talairach space and were interpolated to mm-resolution for display purposes. Note that only frontal coordinates entered the meta-analyses.

Conclusion

By employing a quantitative meta-analytic approach, we were able to show that the IFJ is involved consistently in switching and Stroop studies. This suggests that there is a cognitive process intimately related to IFJ activations that is common to both paradigms. Based on our previous studies (Brass et al., 2002, 2004), we termed this process 'updating of task representations'.