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RESEARCH****Research Report****Intuitive interference in quantitative reasoning****Ruth Stavy^{a,*}, Vinod Goel^b, Hugo Critchley^c, Ray Dolan^c**^aDepartment of Science Education, School of Education, Tel Aviv University, Tel Aviv 69978, Israel^bDepartment of Psychology, York University, Toronto, Ontario, Canada M3J 1P3^cWellcome Department of Cognitive Neurology, Institute of Neurology, Queen's Square, London WC1N 3BG, UK

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ABSTRACT

It is well known that surface features of a task can queue multiple reasoning strategies. Interference or conflict among the strategies is signaled by increasing reaction times and error rates. To determine the neural basis of this interference, we studied 14 volunteers using event-related fMRI, as they compared the perimeters of geometrical shapes in congruent (where the shapes' perimeter changed in the same direction as its area) and incongruent (where the shapes' perimeter was conserved but its area changed) conditions. We found evidence for the engagement of bilateral parietal lobe systems during congruent trials and incorrect incongruent trials. Activation of bilateral orbital frontal cortex was evident when subjects inhibited interference associated with processing the salient feature 'area' and correctly completed the perimeters in the incongruent condition. Varying the level of interference exerted by the unattended feature 'area' (filled vs. unfilled shapes) affected the relative level of activation of right parietal regions but not orbital frontal cortex suggesting that the former is responding to the degree of facilitation while the latter is responsive to the presence of conflict (rather than the degree of conflict).

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1. Introduction

It is well known that surface features of a task can queue multiple parallel strategies (Evans, 1996; Evans, 2003; Goel and Dolan, 2003; Sloman, 1996; Stavy and Tirosh, 2000). Consider, for example, the Rectangle and Polygon task used by Stavy and Tirosh (2000): If we take two geometrical shapes one a rectangle and the other an identical rectangle, from which a small square is removed (for example, from the upper right corner), the area of the rectangle is larger than that of the derived polygon, but their perimeters are equal (Fig. 1). When young adults (17–18 years old high school students) were presented with these tasks, practically all of them (98.5%) correctly responded to the comparison of area task but 46%

incorrectly claimed that the perimeter of the rectangle was longer than that of the derived polygon. Subjects' explanations that the perimeter of the rectangle was longer generally took the form "the rectangle is larger", "has more area", "a corner was not taken away", etc. suggesting that they are using a strategy that we might call the "more A (size/area of rectangle)–more B (length of perimeter)" strategy (Azhari, 1998; Stavy and Tirosh, 2000). These types of responses were regarded as intuitive because they are immediate (Babai et al., *in press*), and are given with high confidence (Fischbein, 1987). Responses in line with this intuitive rule are often correct as everyday life offers many opportunities in which a perceptual difference in one quantity (A) serves as a criterion for comparing another quantity (B). However, when this rule is

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Fig. 1 – Experimental design. Subjects performed one task, in one session that required a comparison of perimeter length of two shapes presented sequentially. Subjects had to decide whether the perimeter of the second shape was larger/equal/smaller than that of the previous shape. They responded by pressing the appropriate button in a response box: the left button for the ‘smaller’, the middle button for ‘equal’ and the right for ‘larger perimeter’. There were two types of shapes unfilled and filled, and two conditions congruent where area and perimeter changed in the same direction and incongruent where area changed and perimeter stayed the same. The first shape was presented for 1000 ms; the second shape was presented for 3000 ms during which the subjects had to press the button of their choice. There was an inter-stimulus interval of 500 ms.

at variance with logic and mathematics, it leads to incorrect judgments.

The explanation offered for this pattern of results is the following: subjects can respond to this task by either attending to the area or perimeter of the rectangle. The area seems to be the more salient feature for most subjects (Azhari, 1998; Stavy and Tirosh, 2000; Babai et al., in press). Subjects probably process both features simultaneously, with faster processing of ‘area’ information (Babai et al., in press). When the processing of area and perimeter results in the same conclusion (e.g., larger area and larger perimeter), a condition

that we will refer to as congruent, this is de facto the end of the processing and the subject can respond. If the result is two different conclusions (e.g., larger area–equal perimeter), a condition that we will refer to as incongruent, the created conflict has to be resolved either by overcoming or inhibiting the irrelevant component of the processing stream or by giving incorrect response relying on the area input.

Having noted the robust behavioral data on strategy interference, we set out to explore the functional neuroanatomy of this process using the rectangle and polygon task described above. We predicted enhanced activation in parietal regions in congruent trials because they are known to be associated with visual and spatial processing and implicated in the comparison of continuous quantities (Pinel et al., 2004; Fias et al., 2003; Tang et al., submitted for publication). In addition, we predicted prefrontal regions to show enhanced activity for correct responses in incongruent trials where there was a conflict between responses generated by processing area and perimeter, because prefrontal cortex is known to be associated with inhibitory executive control over posterior and subcortical brain regions during resolving interference tasks (e.g., Goel et al., 2004; Houde et al., 2000; Hazeltine et al., 2003).

2. Results

2.1. Behavioral data

As expected, the rate of success in congruent trials was higher than in incongruent ones. Most errors were in line with the intuitive rule: larger area–larger perimeter. Reaction times for correct responses in congruent trials were shorter than in incongruent ones. Table 1 shows rates of success and means of medians of reaction times for correct responses in each of the experimental conditions and salience levels.

A 2×2 repeated measure ANOVA was conducted on mean rates of success. The factors were condition (congruent and incongruent) and salience (filled or unfilled shapes). The findings were: a significant main effect of congruency ($F = 21.223$; $df = 13$; $P = 0.00$) where success rate in congruent trials was higher than in incongruent ones; a significant main effect of salience ($F = 7.698$; $df = 13$; $P = 0.016$) where rate of success for unfilled shapes was higher than for filled shapes.

Table 1 – Rate of success and reaction times (ms) in the different conditions ($N = 14$)

	% correct (standard error of mean); intuitive error ^a	Reaction time–mean of medians (standard error of mean)
Congruent	91.6 (2.5)	1184 (64.4)
Filled shapes	90.9 (2.3)	1132 (42)
Unfilled shapes	92.5 (2.2)	1231 (61)
Incongruent	65 (6.8); 25	1454 (110.3)
Filled shapes	62.4; 30 (6.4)	1441 (86)
Unfilled shapes	67.6; 20.5 (6.6)	1418 (94)

^a Intuitive error is an error based on area input, e.g., larger perimeter judgment when area is larger.

A 2×2 repeated measure ANOVA was also conducted on mean reaction times with identical factors to the above namely condition (congruent and incongruent) and salience (filled or unfilled shapes). The ANOVA revealed a significant main effect of congruency ($F = 9.580$; $df = 13$; $P = 0.009$): reaction time for incongruent trials was longer than those of congruent ones.

2.2. Functional imaging data

In terms of functional imaging data, we examined activations associated with correct congruent trials, correct and incorrect incongruent trials and the role of salience. Each is described below. The number of correct trials varied from subject to subject and from condition to condition. However, the numbers of correct responses in both incongruent ($M = 52$ trials) and congruent ($M = 44$ trials) conditions were sufficient for reliable results.

2.2.1. Activation associated with correct congruent trials

The contrast between correct congruent vs. correct incongruent trials revealed activity in bilateral parietal lobules BA 40 (60, -34, 28, $Z = 4.09$) and (-56, -34, 26, $Z = 3.25$) (see Table 2 and Fig. 2), Rt. lingual gyrus BA 18 (10, -68 -6, $Z = 3.77$), Lt. cuneus BA 18 (-10, -92, 16, $Z = 3.50$), Rt. cingulate BA 31 (14, -32, 40, $Z = 4.37$) and Rt. posterior insula (sublobar 32, -18, 8, $Z = 3.46$).

Table 2 – Areas of activation

Anatomy (BA)	Z score	x	y	z
<i>Congruent correct–incongruent correct</i>				
Rt. cingulate gyrus (BA 31)	4.37	14	-32	40
Rt. inferior parietal lobule (BA 40)	4.09	60	-34	28
Rt. lingual gyrus (BA 18)	3.77	10	-68	-6
Rt. white matter	3.68	30	-12	3
Lt. cuneus (BA 18)	3.50	-10	-92	16
Rt. posterior insula (sublobar)	3.46	32	-18	8
Rt. lateral sulcus (BA 4)	3.25	48	-18	16
Lt. inferior parietal lobule (BA 40)	3.25	-56	-34	26
<i>Incongruent correct–congruent correct</i>				
Rt. middle frontal gyrus (BA 11/47)	3.69	40	42	-16
Rt. superior occipital gyrus (BA 18)	3.67	26	-80	10
Lt. middle frontal gyrus (BA 10/11)	3.54	-42	52	-14
Rt. insula	3.53	38	22	-8
Lt. inferior frontal gyrus (BA 47)	3.19	-46	38	-16
<i>Incongruent intuitive error–incongruent correct</i>				
Rt. superior parietal lobule (BA 7)	3.53	58	-18	26
Lt. cerebellum	3.53	-28	-44	-38
Rt. postcentral gyrus (BA 2)	3.34	30	-38	56
<i>Incongruent correct–incongruent intuitive error</i>				
Lt. middle temporal gyrus (BA 21)	4.13	-50	-14	-12
Rt. orbital prefrontal cortex (BA 47)	3.20	40	32	-16
Lt. orbital prefrontal gyrus (BA 11)	3.12	-26	36	-12
<i>Interaction: (filled–unfilled)–(incongruent–congruent)</i>				
Rt. inferior parietal lobule (BA 40)	4.60	48	-46	40
Rt. cuneus (BA 19)	3.73	22	-92	30
Rt. inferior parietal lobule (BA 40)	3.50	54	-22	32

Fig. 2 – Activity reflecting differences between congruent and incongruent conditions. Group data are plotted on parasagittal sections of a normalized template structural brain scan derived from one subject, next to error bars showing the size of parameter estimates for correct congruent and incongruent stimuli. (a) A right parietal region showing enhanced activity associated with congruent trials (congruent–incongruent) (60, -34, 28, BA 40); and parameter estimates + standard error for congruent and incongruent conditions; (b) Lateral orbital frontal gyrus showing enhanced activity associated with conflict resolution in incongruent trials (incongruent–congruent) (40, 42, -16, BA 11) and parameter estimates + standard error for congruent and incongruent (Con refers to congruent, Incon to incongruent).

No activations were found in the contrast between intuitive incorrect incongruent trials and correct congruent ones.

2.2.2. Activation associated with correct incongruent trials

The reverse comparison (correct incongruent vs. correct congruent) revealed activation associated with overcoming the interference, specifically the orbital aspects of the middle prefrontal gyri BA 10/11 and BA 11/47 (40, 42, -16, $Z = 3.69$ and -42, 52 -14, $Z = 3.54$) (see Table 2 and Fig. 2) and of Lt. inferior prefrontal gyrus BA 47 (-46, 38, -16, $Z = 3.19$), Rt. superior occipital gyrus BA 18 (26, -80, 10, $Z = 3.67$) and Rt. insula (38, 22, -8, $Z = 3.53$).

2.2.3. Correct vs. incorrect incongruent trials and reversal

Within the incongruent trials, comparison of incorrect trials (in-line with intuitive rule) vs. correct trials (counter-intuitive), revealed activation in Rt. superior parietal lobule BA 7 (30, -38, 56, $Z = 3.34$), Rt. postcentral gyrus BA 2 (58, -18, 26, $Z = 3.53$), and Lt. cerebellum (-28, -44, -38, $Z = 3.35$) (see Table 2 and Fig. 3).

The reverse comparison (incorrect vs. correct trials) revealed activation of bilateral orbital frontal cortex BA 11/47 (40, 32, -16, $Z = 3.20$), and BA 47 (-26, 36, -12, $Z = 3.12$), and Lt. middle temporal lobe gyrus BA 21 (-50, -14, -12, $Z = 4.13$) (see Table 2 and Fig. 3).

Fig. 3 – Activity reflecting differences between correct and incorrect incongruent trials. Group data are plotted on parasagittal sections of a normalized template structural brain scan derived from one subject, next to error bars showing the size of parameter estimates for correct congruent, correct incongruent and incorrect intuitive incongruent stimuli. (a) Parietal regions showing enhanced activity associated with intuitive error in incongruent trials (incongruent error–incongruent correct) (58, –18, 28, BA 7); and parameter estimates + standard error for congruent, incongruent correct and incongruent intuitive error; (b) Lateral orbital frontal gyrus showing enhanced activity associated with conflict resolution in incongruent trials (incongruent correct–incongruent error) (40, 32, –16, BA 47) and parameter estimates + standard error for congruent, incongruent correct and incongruent error (Con refers to congruent, Incon to incongruent and Corr to correct).

2.2.4. Role of salience

Half of the stimuli used in our study had a higher level of salience of the irrelevant feature ‘area’ (filled shapes) than the other half of the stimuli (unfilled shapes). Interaction between filled shapes stimuli and unfilled shapes stimuli in incongruent vs. congruent conditions [(congruent filled–congruent unfilled)–(incongruent filled–incongruent unfilled)] revealed activations of right inferior parietal lobule BA 40 (48, –46, 40, $Z = 4.6$ and 54, –22, 32, $Z = 3.50$) and Rt. cuneus BA 19 (22, –92, 30, $Z = 3.73$) (see Table 2 and Fig. 4). Comparison in the opposite direction revealed no activations.

3. Discussion

The key behavioral result obtained in this study is consistent with previous studies (Babai et al., in press) related to the same task: significant interference of area processing to perimeter judgments in the incongruent condition. In keeping with the results, our discussion will focus on the neural correlates of

congruent (in-line with intuitive rule) and incongruent (counter-intuitive) conditions in this task.

3.1. Congruent (in-line with intuitive rule) vs. correct incongruent (counter-intuitive) trials

The most striking result obtained here is the different patterns of neural activations during reasoning in the congruent and incongruent conditions. Reasoning in the congruent condition where irrelevant salient task feature (area) changed in the same direction as the relevant non-salient one (perimeter), without creating conflict (in-line with intuitive rule: larger area–longer perimeter), activated the bilateral parietal system known to be involved in perceptual and spatial processing including processing related to comparison of continuous quantities, such as found in our task (Fias et al., 2003; Pinel et al., 2004). This activation is likely to reflect both automatic processing of the salient irrelevant feature ‘area’ and in parallel the processing of ‘perimeter’ (Dehaene et al., 1998; Tang et al., submitted for publication) since: (a) the attended feature in question was perimeter; (b) subjects could not have known whether a given trial was congruent or not; (c) in previous studies, reaction time for perimeter comparison in congruent condition was longer than that of area comparison, indicating use of different strategies in area and perimeter comparisons (Babai et al., in press). In this condition, both, processing of area and processing of perimeter lead to the same result.

Reasoning in the incongruent condition where irrelevant salient task feature changed in a different direction than the relevant task feature, and thus created interference and informational conflict (counter-intuitive: larger/smaller area–same perimeter), resulted in longer reaction times and enhanced activation of bi-lateral orbital aspects of inferior

Fig. 4 – Activity reflecting the role of salience. Half of the stimuli used in our study had a higher level of salience of the irrelevant feature ‘area’ (filled shapes) than the other half of the stimuli (unfilled shapes). Group data for the interaction [(congruent filled–congruent unfilled)–(incongruent filled–incongruent unfilled)] are plotted on parasagittal sections of a normalized template structural brain scan derived from one subject, next to error bars showing the size of parameter estimates for correct congruent and incongruent filled and unfilled stimuli showing interaction between congruency and shape indicating that a facilitatory effect of salience in the right inferior parietal lobule (48, –46, 40, BA 40) but little or no inhibitory effect in the frontal cortex (Con refers to congruent, Incon to incongruent, Fill to filled shapes, Fram to unfilled shapes).

frontal cortex as compared with reasoning in the congruent condition. The inferior prefrontal cortex is known for its executive inhibitory control over posterior and subcortical brain regions during processing of different cognitive functions (Faw, 2003; Aron et al., 2004). It is also known to be activated during tasks which require response inhibition (e.g., Konishi et al., 1999; Goel et al., 2004) and in interference tasks (e.g., Houde et al., 2000; Rogers et al., 1999). In the incongruent condition as is the case in the congruent one, initially both area and perimeter are processed. However, in this condition, the results of these two streams of processing reach conflicting results which have to be resolved. We would suggest that, in our task, the orbital frontal cortex's function is to inhibit the automatic unavoidable processing of the interfering feature area in the parietal lobes.

The congruent (in-line with intuitive rule) trials reflect, in our case the automatic, fast and unavoidable processing of the salient irrelevant task feature 'area' which is initially activated in both the congruent and incongruent conditions. This processing does not interfere with the parallel processing of the 'perimeter' in the congruent condition and is therefore not inhibited in this condition. However, in the incongruent condition, it has to be suppressed. Overcoming its interference in the incongruent condition is probably due to the inhibition of this processing by a frontal-parietal neural network, thus enabling the processing of the attended feature. Indeed, no activation was found when comparing incorrect incongruent trials (in-line with intuitive rule) and correct congruent ones; in both, area and perimeter were processed without the first being inhibited. It may be claimed that in the congruent condition people correctly answer the perimeter task basing their judgments on area input only. However, as mentioned above, previous studies (Babai et al., in press; Zilber, 2004) showed that reaction times for comparison of area were shorter than that for comparison of perimeter in the congruent condition. One way to explain this behavioral difference, is to suggest different processing paths for 'area' and for 'perimeter' (Dehaene et al., 1998; Tang et al., submitted for publication). The results of comparing correct and intuitively incorrect incongruent trials reinforce the findings described above. Intuitively incorrect incongruent responses are based on the irrelevant area input and reflect the 'area' processing (larger area–longer perimeter). In accordance with the results described above, it was found to be associated with activation of the parietal lobe. Correct responses to these trials reflect processing related to conflict detection and resolution which were found to be associated with enhanced activity in bilateral orbital frontal cortex.

Varying the level of interference exerted by the irrelevant and unattended feature (filled vs. unfilled shapes) affected the relative level of activation of parietal regions. The imaging data related to the interaction between congruency and shape [(congruent filled–congruent unfilled)–(incongruent filled–incongruent unfilled)] indicate that there is a facilitatory effect of salience but little or no inhibitory effect. The behavioral data suggest that: (a) facilitatory trials are at ceiling, and (b) salience does result in reduced accuracy in inhibitory trials. Taken together, these results suggest that the orbital prefrontal cortex is not responding to the degree of conflict, but to the presence of conflict or to the recruitment of a different

strategy and that the right parietal lobe is responding to the degree of facilitation.

Our results corroborate and extend the findings of previous studies related to interference between parallel strategies (Goel and Dolan, 2003; Babai et al., in press; Tang et al., submitted for publication). In particular, we have shown two distinct patterns of activation associated with congruent (in-line with intuitive rule) and incongruent (counter-intuitive) conditions in a new domain, that of quantitative (geometrical) reasoning. Congruent condition led to activation in inferior parietal regions which we interpret in terms of automatic processing of perceptual input related to the irrelevant salient quantity 'area'. We interpret the lateral orbital frontal cortex activation associated with conflict resolution in incongruent (counter-intuitive) condition as inhibiting the automatic processing of the interfering external feature in the parietal lobe, thus reducing its interference in this condition.

4. Experimental procedure

4.1. Subjects

Eighteen subjects (10 male, 8 female), age ranged 20–38 (mean = 27.3 years, standard deviation = 6.1 years), were recruited from a pool of volunteers who had responded to advertisements both within and outside the university. Volunteers gave informed consent. All subjects had normal or corrected to normal eyesight. Four of these subjects were excluded from the study as they had less than two correct responses in at least one of the eight groups of trials so that the study was carried out with 14 subjects. The study was approved by the Joint Ethics Committee of the National Hospital and Institute of Neurology.

4.2. Tasks

Subjects performed one task, in one session that required a comparison of perimeter length of two shapes presented sequentially (see Fig. 1). Subjects had to decide whether the perimeter of the second shape was larger/equal/smaller than that of the previous shape. Subjects responded by pressing the appropriate button in a response box: the left button for the 'smaller', the middle button for 'equal' and the right for 'larger' perimeter. Half of the subjects used their right hand and the other half their left hand to counter balance for the motor response. Their reaction time and responses were recorded on-line. The task was computer-based. A program written in Cogent (which runs on a MATLAB Version 6.1 platform) was used. Subjects were trained with 30 other similar trials before they entered the scanner, without receiving feedback. Accuracy and reaction time of the practice trials were not recorded.

4.3. Stimuli

The stimuli, presented on a screen situated outside the scanner, were reflected onto a mirror (of size 20 × 9 cm²) placed inside the scanner. In each trial, two shapes appeared one after the other in light green on white background. The first shape was presented for 1000 ms; the second shape was presented for 3000 ms during which the subjects had to press the button of their choice. There was an inter-stimulus interval of 500 ms (Fig. 1).

The stimuli were geometrical shapes similar to the ones described above (rectangles, or shapes derived from rectangles by adding or removing a small square or rectangle). In half of the trials, the shapes were filled (emphasizing the irrelevant property-

area), and in the other half, they were the same shapes but unfilled (colored the same as the background).

There were two experimental conditions: *congruent*, when the shape with larger area was also with the larger perimeter; and *incongruent*, when the perimeters of the two shapes were equal but their areas were different. The total number of trials was 158, i.e., 48 congruent trials, 80 incongruent trials (we expected about 50% errors in this condition therefore we used more incongruent than congruent trials to ensure sufficient number of correct trials for reliable results in both conditions) and 30 blank trials (which were not included in the analysis). Stimuli were presented in a pseudorandom order with the following constraints: the correct response did not appear on the same button in more than three consecutive trials, the experimental condition was not the same on more than three consecutive trials and the type of shapes (filled, unfilled) did not appear more than three consecutive trials.

4.4. Scanning procedure and imaging data processing

Whole-brain fMRI data were acquired on a 1.5 T Magnetom VISION system (Siemens Sonata, Erlangen Germany). Functional images were obtained with a gradient echo-planar sequence using blood oxygenation level-dependent (BOLD) contrast, each comprising a full brain volume of 36 contiguous axial slices 2 mm thickness 1 mm spacing. Volumes were acquired continuously with a repetition time (TR) of 3.24 s. A total of 240 scans were acquired for each participant in one session (approximately 15 min), with the first 5 volumes subsequently discarded to allow for T1 equilibration effects. During fMRI scanning, pupil diameter was recorded on-line by an infrared eye tracker and pulse was monitored. The functional imaging data were preprocessed and subsequently analyzed using SPM2 (Wellcome Department of Imaging Neuroscience; http://www.fil.ion.ucl.ac.uk/spm_spm implemented in MATLAB 6.5.1. Release 13). Individual scans were realigned, time-corrected, normalized to the MNI template with voxels of $2 \times 2 \times 2$ mm³ and spatially smoothed by a 10-mm FWHM Gaussian kernel using standard SPM methods.

Event-related activity for each voxel for each trial type and each subject was modeled using a canonical hemodynamic response function plus temporal and dispersion derivatives. Statistical parametric maps of the *t* statistic (SPM{t}) were generated for each subject. The onset times of each trial were grouped according to trial type (congruent and incongruent correct responses, and errors) and salience level (filled and unfilled shapes).

At the second level, ANOVA model was applied; modeling trial type (congruent, incongruent, and intuitive error trials) and salience level (filled and unfilled shapes).

Threshold significance was set at 0.001 uncorrected for whole brain with a priori regions of interest in parietal regions for congruent condition and prefrontal regions for incongruent conflict resolution.

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