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Research Paper

# The Brain Networks Basis for Deductive and Inductive Reasoning: A Functional Magnetic Resonance Imaging Study

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## ABSTRACT

**Introduction:** Frontoparietal (FPN) and cingulo-opercular network (CON) control cognitive functions needed in deductive and inductive reasoning via different functional frameworks. The FPN is a fast intuitive system while the CON is slow and analytical. The default-interventionist model presents a serial view of the interaction between intuitive and analytic cognitive systems. This study aims to examine the activity pattern of the FPN and CON from the perspective of the default-interventionist model via reasoning.

**Methods:** We employed functional magnetic resonance imaging (fMRI) to investigate cingulo-opercular and frontoparietal network activities in 24 healthy university students during Raven and Wason reasoning tasks. Due to the different operation times of the CON and FPN, the reaction time was assessed as a behavioral factor.

**Results:** During Raven's advanced progressive matrices (RAPM) test, both the CON and FPN were activated. Also, with the increase in the difficulty level of the Raven test, a linear increase in response time was observed. In contrast, during the Wason's selection task (WST) test, only the activity of FPN was observed.

**Conclusion:** The results of the study support the hypothesis that the default-interventionist model of dual-process theory provides an accurate explanation of the cognitive mechanisms involved in reasoning. Thus, the response method (intuitive/analytical) determines which cognitive skills and brain regions are involved in responding.

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## Highlights

- The cingulo-opercular and fronto-parietal networks (FPNs) control cognitive functions and processes.

- The frontoparietal network is a fast intuitive system that utilizes short-time attention which is compatible with type 1 processing. In contrast, the cingulo-opercular network (CON) is an analytical time-consuming system that utilizes attention and working memory for a longer time, compatible with type 2 processing.

- The default-interventionist model of a dual-process theory states that our behaviors are controlled by type 1 processing unless we are confronted with novel and complex problems in which we have no prior experiences.

## Plain Language Summary

The present study examined the activity of two task-based brain networks through performing diffrent type of reasoning tasks. Fronto-parietal and Cingulo-opercular are the two task-based brain networks that are responsible for cognitive control. These two brain networks direct the way to use cognitive skills and executive functions which are necessary to perform cognitive tasks especially higher-order ones as reasoning tasks. Since the two types of inductive and deductive reasoning tasks requier two different bottom-up and top-down cognitive control respectively, different cognitive skills would be needed which affect the activity of fronto-parietal and cingulo-opercular brain networks. Our results showed that through inductive reasoning task which examined by RAVEN, both of the fronto-parietal and cingulo-opercular brain networks were activated but deductive reasoning task which examined by Wason Selection Card test, just the fronto-parietal brain network was activated. It seems that in the case of deductive reasoninf task, there is a higher probability of errors which lead to giving less correct responses. Based on our results, subjects paid not enough attention to details, so had failure to update informations that leaded to responding with errors. Inactivity of cingulo-opercular network through dedeuctive reasoning task clearly showed that the bottom-up cognitive control did not happen successfully. As a result of that, information processing did not proceed properly.

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## 1. Introduction

The reasoning is the process of making inferences from information and proceeds in two ways, induction, and deduction (Hayes et al., 2018; Krawczyk, 2018c). Inductive reasoning uses partial information for the general conclusion, such as a scientific conclusion or understanding of the similarities and differences between subjects (Eichhorn & Kern-Isberner, 2015). In contrast, deductive reasoning uses general facts for partial conclusions, such as understanding rules or cause-and-effect relationships between subjects (Goel, 2007; Rodriguez-Moreno & Hirsch, 2009). The central role of reasoning in human life emphasizes the importance of characterizing neural mechanisms underlying reasoning that provide an enhanced explanation of how cognitive processes lead to correct and incorrect inferences (Evans, 2019). The present study characterizes these neural mechanisms by investigating the task-control brain network activities from dual-process theory models.

Frontoparietal and cingulo-opercular networks (CONs) are two task-based control brain networks with dissociable functions (Dosenbach et al., 2008; Petersen & Posner, 2012). The fronto-parietal network (FPN) supports rapid control and maintains task-relevant information and attention about one or a small number of trials (Dosenbach et al., 2008) and includes the dorsolateral prefrontal cortex (DLPFC) and intra-parietal sulcus (Dosenbach et al., 2007). In contrast, the CON is slow and contributes to the flexible control of goal-directed behaviors, task-switching, working memory capacity, conflict monitoring processes, and sustained set-maintenance activity spanning the entire task epoch (Dosenbach et al., 2007). The CON includes the dorsal anterior cingulate, medial superior frontal cortex, anterior insula, frontal operculum, thalamus, and anterior prefrontal cortex (Cohen et al., 2017; Dosenbach et al., 2008). The cognitive processes required for each task determine the activity of one or a set of brain networks. (Godwin et al., 2017; Petersen & Posner, 2012).

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The dual-process theory claims that two distinct cognitive processes, type 1 and type 2 processing, shape human inferences (Barrouillet, 2011; Evans & Stanovich, 2013). Type 1 processing is intuitive, rapid, automatic, and unconscious, requiring no working memory capacity (Evans & Stanovich, 2013), consistent with the FPN activity definition. In contrast, type 2 processing is analytic, slow, controlled, and conscious that strongly depends on working memory capacity, controlled attention, and conflict monitoring skills (Evans, 2019), consistent with the CON activity definition. The default-interventionist model of the dual-process theory claims that type 1 processing shapes most of our behaviors and type 2 process is activated only in novel complex tasks (Bago & De Neys, 2020; Evans, 2007). In contrast, the parallel-competitive model of the dual-process theory claims that type 1 and type 2 processing act in parallel when faced with any problem, whether complex or straightforward, familiar or unfamiliar (Evans, 2007), which makes this model unable to explain how biased-responding occurs (Stupple et al., 2013). The biased-responding is that type 1 processing produces the response without spending enough time to analyze it (De Neys et al., 2008) and appears in two ways, belief bias, and rule-matching bias (Stupple & Ball, 2008; Stupple et al., 2013). Belief bias is the tendency to be influenced by previous experience in evaluating conclusions. The rule-matching bias is the tendency to relate tasks with the lexical content of the propositional rule.

Task-based functional magnetic resonance imaging (fMRI) studies showed that the dorsal anterior cingulate cortex (dACC) and the anterior frontal cortex (LPFC) are activated when analytical-based reasoning overcomes bias-based reasoning (Wendelken et al., 2008) is involved in relational reasoning. Functional magnetic resonance imaging (fMRI. Specifically, the activity of the rostrolateral prefrontal cortex (RLPFC) is responsible to keep us “on task” (Wendelken et al., 2008) is involved in relational reasoning. Functional magnetic resonance imaging (fMRI via utilizing working memory (Bago, 2018; Bago & De Neys, 2020). The dorsal anterior cingulate cortex (dACC) functions as an online regulator of sustained controlled attention and conflict monitoring (Becerril & Barch, 2013; Sadaghiani & D’Esposito, 2015). Both ACC and LPFC are among the constituent regions of the CON (Sadaghiani & D’Esposito, 2015; Sadaghiani et al., 2010). The fMRI study of people with brain damage who underwent cognitive rehabilitation of strategy-oriented reasoning showed that the CON became more activated and made more connections with the other brain regions (Han et al., 2016). Intellectual performance in reasoning tasks depends on the functional interplay between the CON with other brain networks (Cocchi et al., 2014). Moreover, replacing biased responding with analytical responding depends on consuming enough time for analysis that demonstrates type 2 processing overrides type 1 processing, consistent more with the default-interventionist model (Greene et al., 2004). Previous findings are significant but no consensus still exists on a model.

The lack of sufficient neurocognitive evidence in previous studies is one of the reasons that caused controversy. Another reason is the use of two types of deductive and inductive reasoning tests, which were strongly dependent on the semantic content and the existence of similar previous experiences (Krawczyk, 2018b, Krawczyk, 2018a; Rips, 2001) people can evaluate arguments in at least two qualitatively different ways: In terms of their deductive correctness and in terms of their inductive strength. According to a second view, assessments of both correctness and strength are a function of an argument’s position on a single psychological continuum (e.g. subjective conditional probability. Such conditions increase the likelihood of biased responses and consequently type 1 processing activity (Evans, 2019; Janssen et al., 2021), which leads to underestimation of reasoning skills. Since two separate cognitive systems underlie type 1 and 2 processing, it can be helpful to study neural network activities via reasoning tasks that minimize the likelihood of biased responses. In this regard, we hypothesized that in responding away from biases, the type 2 process overrides the type 1 process based on the default-interventionist model. Accordingly, in addition to the FPN activity, the CON activity and increasing response time are expected. We employed fMRI to test this hypothesis to compare task-control brain network activation during inductive and deductive reasoning tasks.

## 2. Materials and Methods

Twenty-nine right-handed university students aged 18 to 30 years (15 females: Mean±SD 25.7±2.5) with normal or corrected-to-normal vision participated in this study. Two female and three male participants were excluded from the analysis due to head motion of more than 2 mm during fMRI acquisition. Participants had no history of the disorder (medical, neurological, psychiatric) and did not use alcohol and drugs at the time of the study. Written informed consent to participate in the study was obtained from all participants and an amount was disbursed as a cost of participating in the study.

## Measures

### Deductive reasoning

To assess deductive reasoning, the conventional version of Wason's selection task (WST) (Cocchi et al., 2014) for fMRI was used. In the Wason test, a cause-and-effect process is proposed based on conditional rules, in which partial conclusions are made based on a general fact. As a result, the participant is required to consider the possible consequences of a fact and make decisions via the top-down processing paradigm, consistent with the deduction definition (Cutmore et al., 2015; Krawczyk, 2018a). The Wason's selection card test comprises three parts, general statement, conditional statement, and probe symbols. The statement describes that each card has two sides with a single-digit number (1-9) on one side and a non-hybrid English letter on the other side. Participants were especially informed that the conditional statement was not bidirectional. For example, when it is said, "if A then 7," it does not mean "if 7 then A". Each conditional statement consisted of four question modes (two letters and two numbers) and a non-alphanumeric letter, such as "#" which was unrelated to the task's rule and was considered as a control condition. Figure 1 shows Wason's selection test design. As a whole, nine different conditional rules were presented during the experiment. Each trial started with a short- blank screen for 200 ms, immediately after a central fixation cross (+) presented for 800 ms which was followed by a blank screen displayed for 4000 ms. Then the logical rule (conditional statement) displayed for 3000 ms establishing the relation between variables (e.g. "if A then 7"). After the conditional statement, a long-blank screen was presented in a randomly varied period of 3000-5000 ms. Subsequently, the probe symbol was presented for 3000 ms. In the probe symbol presentation, each card contained either a number or a letter (i.e. one of the possible five modes, "p", "q", "not-p", "not-q") and or a non-alphanumeric symbol (e.g. "#" considered as control). Then, a screen with two options "yes" and "no" was displayed for 4000-6000 ms and participants were instructed to determine, as quickly and accurately as possible, if the presented card was potentially able to "disconfirm" the rule. For example, if the conditional statement was "if A then 7", then, based on the statement, 5 cards included, "A" was considered as p, "7" considered as q, "any digit other than 7 like 3" was considered as not-q and "any letter other than A like G" was considered as not-p and a non-alphanumeric symbol, which was unrelated to the given conditional rule. Given our example rule (if A then 7), If the card with the symbol "A" is turned over and the number "7" appears, the conditional statement is confirmed, and it is not confirmed with any number other than 7. Therefore, the symbol "A" card can disconfirm the conditional rule. However, since the conditional rule is not bidirectional, the inference "if 7 then A" can't be concluded. As a result, if the card with the symbol "7" is turned over and any letter other than "A" be on the reverse side, it is not against the conditional rule and cannot disconfirm it. The card with the symbol "G" can neither confirm nor disconfirm the conditional rule because no information is found about it in the conditional proposition. If the symbol "A" appeared on the reverse side of the card with the symbol "5", the conditional rule is disconfirmed. Because according to the conditional proposition, only

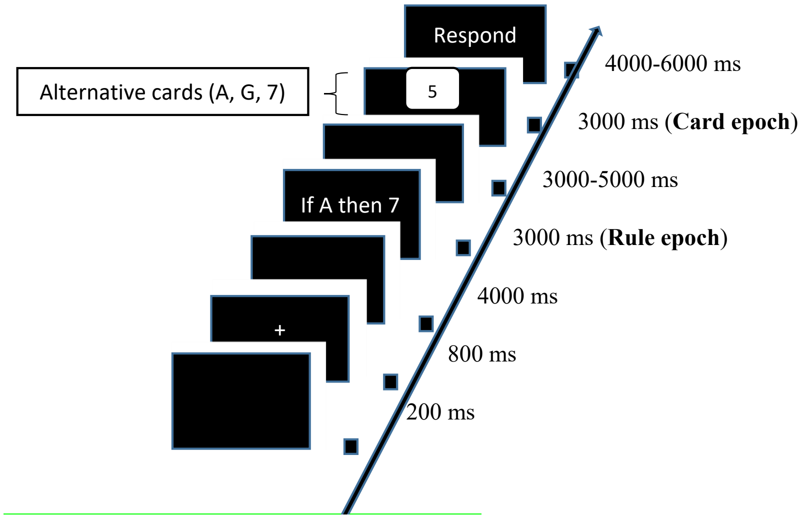

**Figure 1.** The timeline of the presentation of Wason's selection test

Participants selected between the response "yes" and "no".

the number “7” is expected to be on the reverse side of the symbol “A.” Therefore, the card with the symbol “5” can disconfirm the conditional proposition. As a result, to make the right choice, all possibilities behind each card must be considered first, and then it must be determined whether it contradicts the conditional rule or not. Contradiction with the conditional rule means the ability to disconfirm the rule.

### Inductive reasoning

To assess inductive reasoning, we used Raven’s advanced progressive matrices (RAPM) (Desco et al., 2011). In the Raven test, by following the partial changes through rows and columns of matrices, the general change paradigm can be discovered. This process is formed by comparing the similarities and differences between the figures via the bottom-up processing paradigm consistent with the induction definition (Klauer & Phye, 2008; Rasmussen & Eliasmith, 2014; Waschl et al., 2016). Accordingly, in the Raven matrices test, comparing the differences and similarities between the shapes leads to discovering the general rule. The structure of RAPM consists of 3×3 matrices of figures that always the bottom right figure is missing and the participant should choose the correct answer from eight response choices. Due to response box limitations, we simplified our version so that, after considering the correct answer option, a psychologist was asked to choose three options randomly with no bias to make the question harder or easier. Each trial consisted of 4 choices instead of the standard number of 8 presented below the matrix. Participants were asked to complete the missing part. To design a control task for this test, we used 3×3 matrices of simple and identical geometric figures with the bottom right figure missing. Since the figures were identical, completing the control task did not require identifying the relationship between the figures. Figure 2 shows the RAPM test design. After pressing the response button, a new trial was presented. The response time was the duration between the appearance of the task and the response. The maximum response time was 20 s and if no response was given, the next trial was presented automatically, the trials with no responses were registered as missing responses. The test began with 9 control trials and then 4 task trials were presented. This arrangement continued until the end of the test. Based on fMRI sequence time, blocks were alternated for 7 minutes and 30 s. Since the participants had different response times, the total test time varied across participants.

## Procedure

This study was a fundamental cross-sectional neuroimaging research. Participants who met the inclusion criteria were examined by a physician to confirm their physical and mental health. After signing the consent form, participants underwent a training program about how to do reasoning tasks inside the MRI scanner. The training session lasted until their performance reached at least 60% of accuracy. The task was initiated with a white blank screen as a block of rest to make sure that the hemodynamic response function is back to the true baseline after starting the sequence (10 s). Then the Raven and Wason tests were displayed and the order of performing was random. The task Raven and Wason tests were programmed by Psychtoolbox in Matlab software, version 4.2 which registered behavioral data, including the number of correct, incorrect, and missing responses and reaction times (milliseconds).

## Functional magnetic resonance imaging (fMRI) procedure

During the experiment, the stimuli were projected onto a viewing screen located at the head end of the MR scanner tunnel. Data were conducted on a 3T Siemens MRI scanner and a 20-channel head coil used. For each participant, a structural T1 image was acquired (gradient-echo; TR (time repetition)=3000 ms; TE (time to echo)=9.2 ms; matrix size=256×256×175; flip angle=30; slice thickness=1 mm; and voxel size=1×1×1 mm m). The fMRI phase used a T2*[1] -weighted echo-planar sequence with the following parameters: TR=3000 ms, TE=50 ms, matrix size=64×64×20, flip angle=90, voxel size=3.6×3.6, slice thickness=5 mm, and 20 axial slices. For each task, the fMRI acquisition lasted for 7 minutes and 30 s (150 functional images, one every 3 s).

## Preprocessing

Image preprocessing and analysis were performed in the FMRIB Software Library (FSL) software. Functional images were corrected for acquisition time (slice timing) and echo planar imaging volumes were realigned. Then, images were spatially normalized to a standard neuroanatomical space defined by the Montreal Neurological Institute (MNI). Results were visually checked and 5 participants were excluded using a criterion of 2 mm of displacement. Normalization parameters were estimated using the mean image for

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[1] Refers to the decay of transverse magnetization seen with gradient-echo (GRE) sequences. T2 relaxation only reflects the decay of the transverse magnetization vector of the tissue itself. However, T2* relaxation does not use the 180° refocusing pulse to focus the pulses but uses it to switch the gradient field to generate the signal reunion.

each run and were applied to all volumes of that run. The fMRI analyses were performed using the FMRIB Software Library (FSL) software package with standard processing. This includes brain extraction, temporal high-pass filtering (90 s), 4D mean intensity normalization, spatial smoothing at 6 mm full width at half maximum (FWHM), slice timing correction, MCFLIRT (MC+F+LIRT: Intra-model motion correction tool based on FMRIB's linear image registration tool) motion correction, and registration of functional MRI to respective high-resolution anatomical T1 image and the standard Montreal Neurological Institute (MNI) template 152 space via FNIRT (FMRIB's non linear image registration tool). The registration process allowed data from each participant to be spatially aligned on a standard brain template for comparison. The suject-level and group-level analysis of "the RAPM test and Wason selection card test" were completed using a z score greater than 2.3 and a (corrected) cluster significance threshold of P=0.05.

### Statistical analysis

The statistical analysis was based on a general linear model in event-related design analysis. The effects and significance assessed voxel-wise using linear contrast (t-test). Contrast images for the individual subjects were analyzed within-subject and within-group (first level) and then between-group (second level). Gender effects were not included in the analysis model. To correct multiple comparisons, we used family-wise error (FWE) criteria, and statistical maps were assessed for voxel-wise significance using FWE voxel and cluster threshold of P=0.001. The between-group comparison analyses (Raven versus Wason) were threshold using an FWE-corrected P of 0.05 with a cluster size threshold of 10 voxels. The mean statistic was used to compare descriptive data. The chi-square statistic was used to compare the correct responses, and repeated-measure analysis of variance (ANOVA) was used to compare the mean response time of Wason's test questions.

## 3. Results

### Behavioral performance

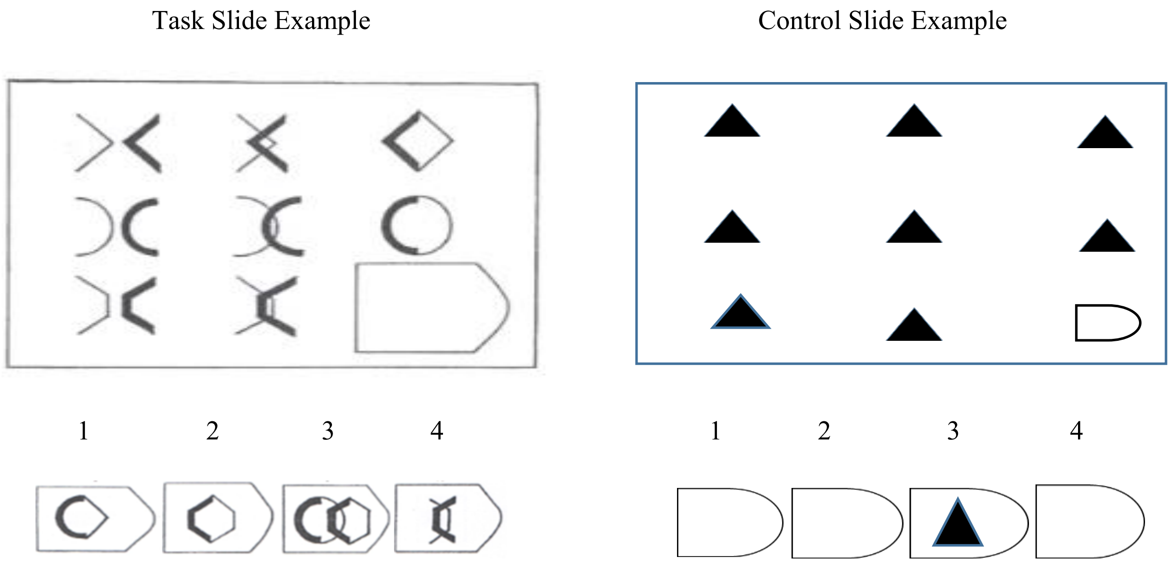
Table 1 presents the behavioral performance of the subjects in the Raven and Wason tests. The differences between the number of correct, incorrect, and missing responses between the two tasks are not statistically significant.

Figure 3 shows the mean changes in response time during the Raven test from question 1 to question 36. As the difficulty of the RAPM test questions increased, the time required to answer the questions also showed a linear increase.

### Functional magnetic resonance imaging (fMRI) results

#### Brain activation during inductive reasoning task

Significant activation of the contrast was found among RAPM task condition versus control condition in the following areas, posterior parietal lobe (BA 7), superior parietal lobe (BA 5), inferior occipital lobe (BA 17) and percuneus, lateral occipital gyrus (BA 18/19), infe-


Task Slide Example

Control Slide Example

**Figure 2.** Examples of activation and controls trials in PARM tasks

Participants selected the correct response by pressing one of four available buttons.

**Table 1.** Mean±SD of behavioral data during RAPM and WST

| Variables | Mean±SD | | P |
|---|---|---|---|
| | RAPM | WST | |
| Correct responses (%) | 44.7±11.6 | 58.4±16.4 | 0.6 |
| Incorrect responses (%) | 26.8±6.7 | 16.1±4.7 | 0.1 |
| Missing responses (%) | 26.7±5.3 | 25.5±7.3 | 0.7 |

RAPM: Raven advanced progressive matrices; WST: Wason's selection test.

rior frontal gyrus (BA 11), bilateral activation in middle frontal gyrus (BA 9/10/46), anterior cingulate gyrus (BA 32/24), insular cortex and Bilateral activation in the fusiform gyrus (BA 37), (Table 2, Figure 4).

The LPFC, RLPFC, the insular region, the thalamus, and the posterior-anterior cingulate area form the CON. The DLPFC, RLPFC, lateral frontal area (LFC), and parietal regions form the FPN. The activity of both the fronto-parietal and singulo-opercular networks is observed during the Raven test. It should be noted that RLPFC is common between both FPN and CON (Figure 5).

## Brain activation during deductive reasoning task

A significant activation of the contrast was found during the Wason selection cards task condition versus the control condition in the following areas, precuneus (BA 7), postcentral gyrus (BA 1/2/3), superior parietal loboule (BA 5/7), inferior parietal loboule (BA 40), angular gyrus (BA 39), posterior parietal cortex (BA 7), middle frontal gyrus (BA 9/10/46), precentral gyrus (BA 4), superior frontal gyrus (BA 6), inferior frontal gyrus (BA 11), the cerebellum anterior lobe, culmen (vermis 4/5), cerebellum posterior lobe, declive (vermis 6), cerebellum posterior lobe, pyramid (vermis 8), (Table 3, Figure 6).

The DLPFC, RLPFC, lateral frontal area (LFC), and parietal regions form the FPN. During the Wason test, only the activity of the FPN was observed.

To capture precise neural components underlying the correct responses of conditional reasoning, a post-hoc contrast was made among the time series of correct responses and control conditions. This contrast showed activation in the inferior parietal loboule (BA 40), angular gyrus (BA 39), middle frontal gyrus (BA 9/46), precentral gyrus (BA 4), superior frontal gyrus (BA 6), and inferior frontal gyrus (BA 11) (Figure 7).

Activated brain regions during the correct response of Wason's selection card test only showed the activity of FPN (Table 4).

To precisely investigate the participant's responses to the four modes of the Wason test question, the average number of correct responses and the average response time were shown

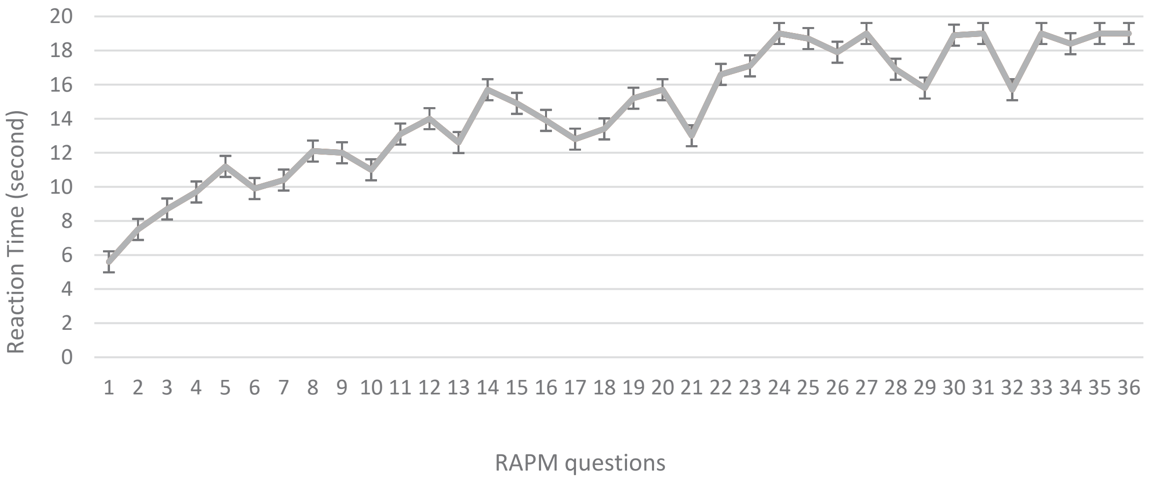


**Figure 3.** Line graph depicting mean response time when performing RAPM from question 1 to question 36

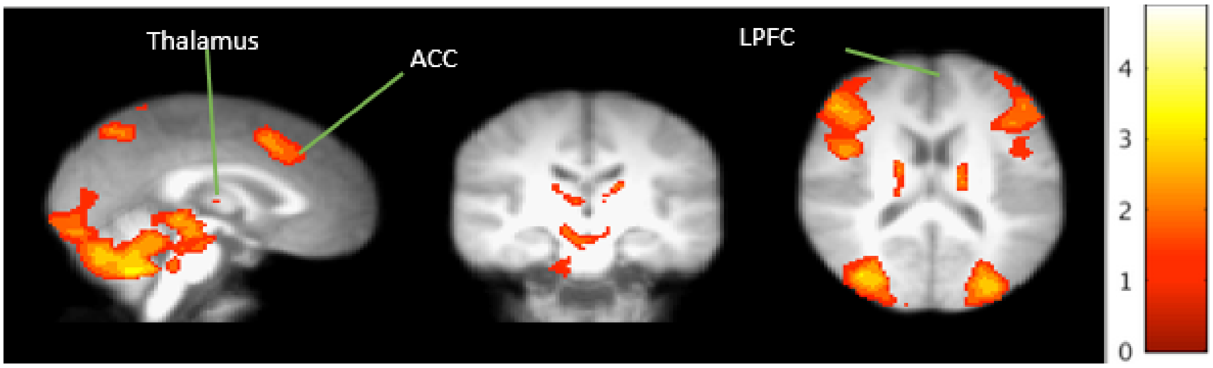


**Figure 4.** Activation maps in response to performing RAPM test

ACC: Anterior cingulate cortex; LPFC: Lateral prefrontal cortex.

(Figure 8). The average percentage of correct responses in the four modes of the Wason test question; p, q, not-p, and not-q were 82, 43, 76, and 37, respectively. The average response time was 4.1, 4.6, 4.3, and 4.4 s, respectively. The chi-square test on the percentages of correct responses was not significant. The repeated-measure analysis of variance (ANOVA) test on the mean reaction times was not significant ($P<0.05$).

## 4. Discussion

The present study was conducted to clarify whether the cognitive mechanisms involved in reasoning are explained by the default-interventionist model of the dual-process theory. We hypothesized that if responding happens away from biases, the type 2 process over-

**Table 2.** Activated brain regions during the inductive reasoning test of RAPM

| Region of Significant Activation Contrast (t-test) Task>Control | | | | | | | |
|---|---|---|---|---|---|---|---|
| Brain Regions | Local Maxima | | | | | | |
| | hem. | BA | X | Y | Z | Z. Score | K |
| Inferior occipital lobe | R | 17 | 50 | -84 | -6 | 7.14 | 3561 |
| lateral occipital cortex | L | 19/18 | -32 | -88 | -14 | 7.04 | |
| Fusiform | L | 37 | -44 | -70 | -14 | 7.11 | |
| superior parietal lobule | R | 5 | 26 | -66 | 48 | 7.07 | |
| Posterior parietal lobe | R | 7 | 46 | -72 | -18 | 7.07 | 4685 |
| RLPFC; inferior frontal cortex | L | 11 | -50 | 8 | 30 | 6.08 | |
| RLPFC; middle frontal cortex | L | 10 | -46 | 12 | 34 | 5.58 | 3311 |
| DLPFC; middle frontal cortex | R | 9/46 | 50 | 36 | 16 | 6.14 | |
| Anterior cingulate cortex | L | 32 | -2 | 14 | 48 | 5.65 | 1050 |
| Posterior cingulate cortex | R | 24 | 12 | 20 | 46 | 4.83 | |
| Insula | R | 13 | 34 | 16 | -4 | 5.53 | 468 |
| Thalamus | | | -15 | -19 | 10 | 4.01 | |

Abbreviations: L: Left hemisphere; R: Right hemisphere; BA: Approximate Brodmann's area; K: Cluster size; RLPFC: Rostrolateral prefrontal cortex; DLPFC: Dorsolateral prefrontal cortex.

Activity coordinates (X, Y, Z) are given in Talairach atlas space.

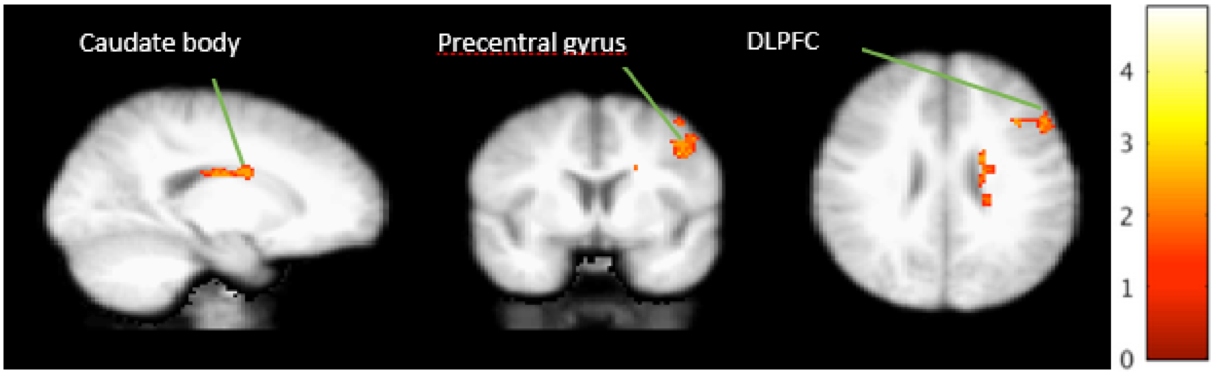


**Figure 5.** Activation maps in response to performing Wason selection card test

DLPFC: Dorsolateral prefrontal cortex.

comes the type 1 process. As a result, in addition to the frontoparietal network activity, the CON activity is expected. The frontoparietal network is one of the large-scale brain networks involved in sustained attention but the point is that this network is fast and keeps information for a short time (Dosenbach et al., 2007). Therefore, if the information processing and updating be required for a longer time, spending more time and having tonic alertness is vital which is related to the CON activity (Sadaghiani & D'Esposito, 2015; Sadaghiani et al., 2010)

**Table 3.** Activated brain regions during the deductive reasoning test of Wason's selection card test

| Region of Significant Activation Contrast (t-test) Task>Control | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Brain Regions** | **Local Maxima** | | | | | | |
| | **hem.** | **BA** | **X** | **Y** | **Z** | **Z. Score** | **K** |
| Precuneus | L | 7 | -28 | -72 | 40 | 4.32 | 1387 |
| Post-central gyrus | R | 1 | 42 | -26 | 66 | 4.22 | |
| Superior parietal lobule | L | 7 | -36 | -50 | 48 | 3.92 | |
| Inferior parietal lobule | L | 40 | -36 | -52 | 48 | 3.88 | |
| Angular gyrus | L | 39 | -36 | -62 | 46 | 3.84 | |
| Posterior parietal cortex | R | 5 | 42 | -24 | 66 | 3.53 | |
| precuneus | L | 9 | -46 | 24 | 30 | 4.02 | |
| DLPFC; middle frontal gyrus | L | 46 | -54 | 22 | 22 | 3.80 | 1175 |
| Precentral gyrus | L | 4 | -48 | 0 | 40 | 3.27 | |
| RLPFC; inferior frontal gyrus | L | 11 | -46 | 0 | 42 | 3.25 | |
| RLPFC; superior frontal gyrus | L | 6 | -50 | 14 | 16 | 4.01 | |
| Cerebellum anterior lobe | L | | -12 | -60 | 4 | 3.96 | 725 |
| Cerebellum posterior lobe | R | | -10 | -62 | -34 | 3.33 | |

Abbreviations: L: Left hemisphere; R: Right hemisphere; BA: Approximate Brodmann's area; K: Cluster size; RLPFC: Rostrolateral prefrontal cortex; DLPFC: Dorsolateral prefrontal cortex.

Activity coordinates (X, Y, Z) are given in Talairach atlas space.

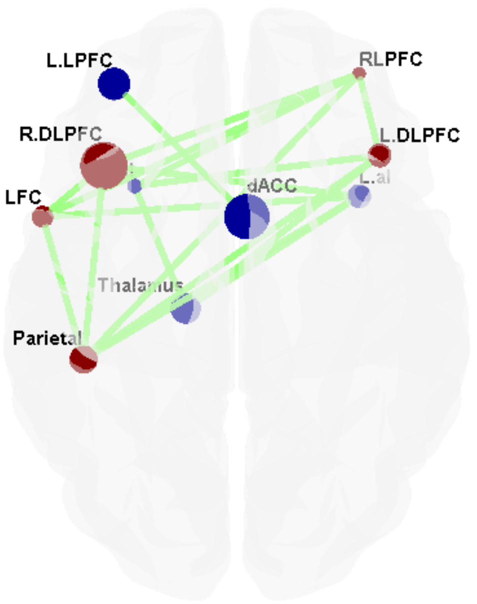


**Figure 6.** Schematic representation of control brain networks, fronto-parietal network (red) and cingulo-opercular network (blue)

Also, with the increase in difficulty level of questions, due to type 2 processing activity, an increase in response time is expected. Our results demonstrate that during the Raven test, both frontoparietal and CON were activated. The CON activity confirms the activity of type 2 processing which depends on utilizing controlled attention and working memory capacity for a long-time. In contrast, the inactivity of the CON during Wason's selection test means that type I processing dominated in responding, which is fast and has no role in utilizing mental resources.

Raven test questions are tough, therefore answering these questions requires many cognitive skills, including sustained attention and working memory capacity (Desco et al., 2011; Masunaga et al., 2008). In addition, Raven's difficulty level is progressive (Waschl et al., 2016), which needs more mental effort (Waschl et al., 2016), therefore type 1 processing will not be able to produce any biased responses. In particular, our results showed the bilateral activity of the hemispheres, indicating more significant accurate responses. It is consistent with studies in which brain bilateral activity patterns during the Raven test were associated with more accurately utilizing mental resources (Rasmussen & Eliasmith, 2014). These results are consistent with the results of a study showing that the CON controls cognitive processes, switching, and communication between brain regions (Dosenbach et al., 2008), thereby replacing automated reactions with analytically controlled reactions (Sadaghiani & D'Esposito, 2015) dorsal anterior cingulate cortex, and thalamus. Its function has been particularly difficult to characterize due to the network's pervasive activity and frequent co-activation with other control-related networks. We previously suggested this network to underlie intrinsically maintained tonic alertness. Here, we tested this hypothesis by separately manipulating the demand for selective attention and for tonic alertness in a two-factorial, continuous pitch discrimination paradigm. The 2 factors had independent behavioral effects. Functional imaging revealed that activity as well as functional connectivity in the CO network increased when the task required more tonic alertness. Conversely, heightened selective attention to pitch increased activity in the dorsal attention (DAT. Suppressing default mode network (DMN) ingulo-opercular network activity was found to decrease the error rate implying more inhibition and monitoring skills consistent with type 2 processing (Chiong et al., 2013). Brain-damaged subjects who underwent analytical strategy-oriented reasoning rehabilitation programs clearly showed increased activity of the CON and its connections with other brain areas (Han et al., 2016) which is consistent with our findings that more detailed analysis and the use of different mental resources are related to CON activity.

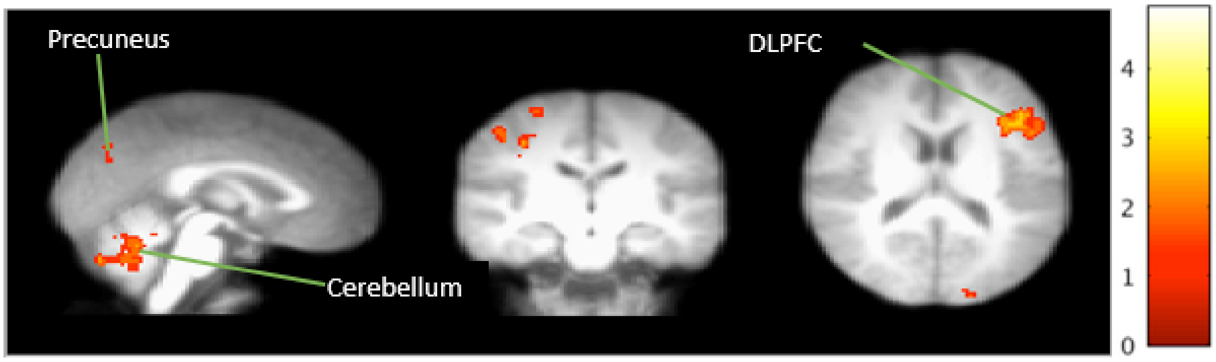


**Figure 7.** Activation maps of correct responses to performing Wason selection card test

**Table 4.** Post-hoc analysis of activated brain regions during correct responses of Wason's selection card test

| Region of Significant Activation Contrast (t-test) Task>Control | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Brain Regions** | **Local Maxima** | | | | | | |
| | **hem.** | **BA** | **X** | **Y** | **Z** | **Z. Score** | **K** |
| Superior parietal lobule | L | 40 | -36 | -60 | 38 | 3.78 | 1387 |
| Inferior parietal lobule | R | 9 | -36 | -62 | 46 | 3.84 | |
| RLPFC; Inferior frontal gyrus | R | 46 | 42 | -24 | 54 | 3.60 | 1175 |
| DLPFC; middle frontal gyrus | L | 6 | -54 | 22 | 22 | 3.80 | |
| Precentral gyrus | L | 11 | -48 | 0 | 40 | 3.27 | |
| Caudate | R | | -18 | -18 | 26 | 3.46 | |

Abbreviations: L: Left hemisphere; R: Right hemisphere; BA: Approximate Brodmann's area; K: Cluster size; RLPFC: Rostrolateral prefrontal cortex; DLPFC: Dorsolateral prefrontal cortex.

Activity coordinates (X, Y, Z) are given in Talairach atlas space.

By increasing the difficulty level of Raven test questions, a linear increase was observed in response time. Our results are consistent with studies that equate increased response time with type 2 processing activity (Bago, 2018; Greene et al., 2004). Overall, the activity of the CON and the linear increase in response time support the view that in the conflict between biased-based reasoning and logical reasoning, type 2 processing is required to discard quick responses and generate logical responses (Bago, 2018; Evans, 2007; Stupple et al., 2013). Thus, the difficulty level of questions predicts the need for type 2 processing in addition to type 1 processing.

In the analysis of brain activity during Wason's selection test, only the activity of the frontoparietal network was observed. The inactivity of the CON means that type 1 processing dominated in responding. The same result was obtained in the post-hoc analysis of brain activities related to the correct responses. We found that most correct responses were for cards with symbols "p" and "not-p" which are the simplest questions of Wason's selection test (Cocchi et al., 2014; Liu et al., 2012). In contrast, the lower percentage of correct responses belonged to cards with symbols "q" and "not-q", which are defined as challenging questions (Cocchi et al., 2014;

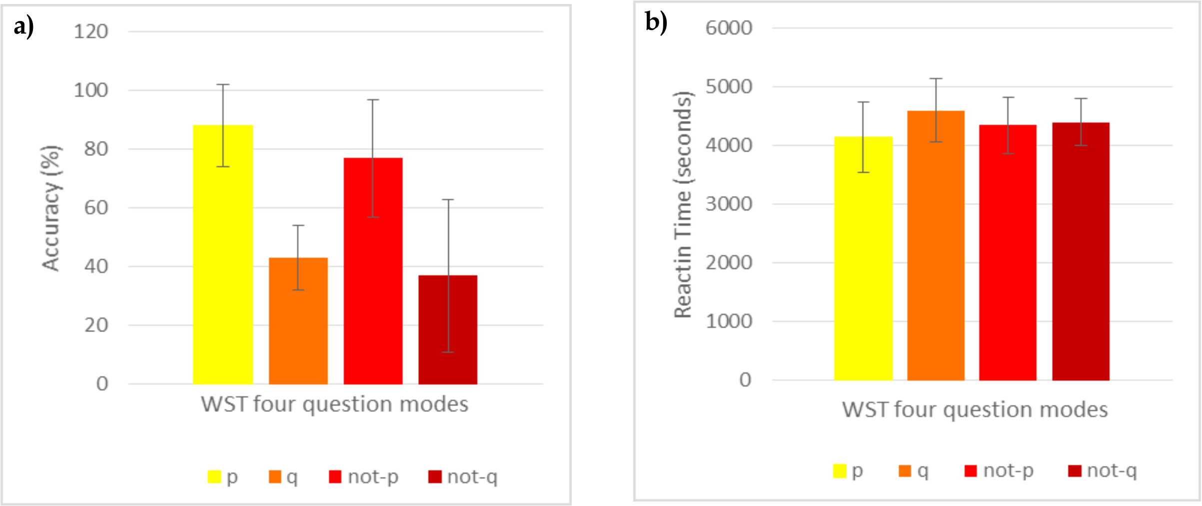


**Figure 8.** Behavioral data obtained during performing 4 card types of Wason's selection card test

a) Mean percentage of accuracy, b) Mean of reaction times

Liu et al., 2012). Although this difference is not statistically significant, it is noteworthy. Choosing the card with the symbol "q" as the card that can disconfirm the conditional rule, while the correct response was the card with the symbol "not-q" showed that the decision was made only based on the lexical information of the conditional rule and not enough attention was paid to the logic of the probabilities behind each card. This responding pattern is precisely compatible with the rule-matching bias (Evans & Ball, 2010), which is the salient feature of type 1 processing (Frankish, 2010; Stupple et al., 2013). Therefore, participants respond solely based on the lexical information of the conditional rule (Bago & De Neys, 2020) without paying attention to the logic behind the questions (Goel, 2007). Our results are consistent with another study in which using the effective connectivity method has shown that intellectually accurate performance in deductive reasoning needs the dynamic relationship between frontoparietal and CONs (Cocchi et al., 2014). The frontoparietal network activity represented the neural basis of the generation of conclusions in elementary deductive reasoning problems; therefore, it will not be enough to answer challenging reasoning problems (Liu et al., 2012; Reverberi et al., 2010). The CON's inactivity showed not enough controlled attention and in-depth analysis.

The cards with the symbols “q” and “not-q” were expected to take longer response time (Stupple et al., 2013) compared to others while investigating the spent time showed no significant differences. It can be concluded that where the question became more difficult and required more time for in-depth analysis, the process has not gone correctly, and as a result, type 1 processing (quick biased-responding) prevailed (Evans, 2019). In the present study, the inactivity of the CON and the lack of more response time in responding to difficult questions indicate that type 1 processing was responsible for responding. Therefore, only the activity of the frontoparietal network was observed.

## 5. Conclusion

In the current study, we examined the accuracy of default-interventionist and parallel-competitive models of dual-process theory from the view of control brain networks. Based on findings, the activity of both frontoparietal and CON during the Raven test and the inactivity of the CON during the Wason test showed that sometimes one type of processing overcomes the other. Therefore, the parallel-competitive model, which states that both types of processing are activated simultaneously and in parallel, is not correct. Therefore, the default-interventionist model provides a more comprehensive description of the dual-process theory that states type 1 processing begins responding until confronting new and challenging problems, in which more analytical and consequently type 2 processing is needed.

### Limitation

Since reasoning skills, specifically inductive reasoning, are directly related to fluid intelligence, the lack of classification of participants’ intelligence levels was one of the limitations of the present study. It is suggested that future studies be carried out in a set of inductive and deductive reasoning tests that lead to comprehensive conclusions.

## Ethical Considerations

### Compliance with ethical guidelines

The present study protocol was approved by “the Ethic Committee of the Institute for Cognitive Science Studies” (Code: IRIcff.1398.002).

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### Authors' contributions

Conceptualization and methodology: Mehdi Tehrani-Doost and Reza Khosrowabadi; Investigating software results: Reza Khosrowabadi; Data collection, formal analysis, data acuration and resources: Seyyedeh Fatemeh Seyyed Hashemi; Writing the original draft: Seyyedeh Fatemeh Seyyed Hashemi and Reza Khosrowabadi; Supervision, administration, review and editing: Mehdi Tehrani-Doost.

### Conflict of interest

The authors declared no conflict of interest.

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