RUDN Journal of Psychology and Pedagogics
Вестник РУДН. Серия: Психология и педагогика
ISSN 2313-1683 (Print); ISSN 2313-1705 (Online)
2023 Vol. 20 No. 3 578–587
http://journals.rudn.ru/psychology-pedagogics

DOI: 10.22363/2313-1683-2023-20-3-578-587
EDN: AJYYHJ
UDC 159.91

Research article

A Group Level Analysis of Self-evaluations Associated with Cognitive Load

Alexios Kouzalis

HSE University,
20 Myasnitskaya St, Moscow, 101000, Russian Federation
alexiskouzalis@gmail.com

Abstract. Self-evaluation, or self-rating, is the process by which people evaluate themselves with the purpose of improving several aspects of their personalities or skills and it is closely related to the cognitive function of metacognition. The purpose of the study was to investigate the degree of implication of various brain areas to meta-cognition as it relates to subjective ratings of cognitive effort when performing mathematical problems of different complexity. To achieve this, participants were recruited to solve mathematical problems (addition, subtraction, multiplication, and division) in three levels of difficulty, while inside an fMRI scanner. After solving a given task, they were asked to evaluate the amount of effort they spent to solve it. Brain signal was collected during their answers, which was then analyzed with the aid of computer software. Results of the analysis show that increases in task difficulty activate the frontal lobe, cingulate and insular cortex areas. The parietal lobule, the precuneus and the cingulate gyrus were found to be active as well as during all four mathematical operations.

Key words: cognitive load, self-evaluation, neuroimaging, group-level analysis

Acknowledgements and Funding. Support is gratefully acknowledged in part from the Russian Science Foundation no. 17-18-01047 and in part from the Russian Foundation for Basic Research project no. 19-313-51010.

Introduction

Self-rating is driven by several motives. The need to have a positive impression of ourselves, the need to be certain about our abilities and not blinded by illusion and the need to keep verifying ourselves as new situations arise that put our self-image to the test (Sedikides, 1993). “Cognitive load” is the used amount of working memory resources according to cognitive load theory (Sweller, 1988). This effort can be objectively and subjectively assessed using the demand of the task and self-ratings of the individual. Objective assessments have a single correct answer whereas subjective assessments may have more than one possible answer. Metacognitive ability of memory and perception seems to depend on gray matter volume (Baird et al., 2015). The prefrontal cortex is mainly responsible for metacognitive processes, but evidence suggest that the insular and anterior cingulate cortices are also involved in this process though their interaction with the prefrontal cortex (Fleming, Dolan, 2012). Regions of the prefrontal cortex (Baird et al., 2013; D'Argembeau et al., 2007; Fleming, Lau, 2014; Morales et al., 2018) and the insula (Van der Meer et al., 2013; Spalletta et al., 2014) had been found in many previous neuroimaging studies to be involved with metacognition.

Other brain areas, such as the claustrum (Arsalidou, Taylor, 2011), the anterior cingulate cortex (Fleming, Dolan, 2012) and the locus coeruleus (Fechir et al., 2010) have also been speculated to be involved in metacognition. Brain regions that activate during confidence assessment typically deactivate during cognitive tasks (Chua et al., 2006). Regions that are not activated by metacognition, metamemory or metadecision can be used as control regions. These are parts of the occipital lobe involved in vision and reading such as the primary and secondary visual cortices. Other parts irrelevant with metacognition are the primary motor cortex, the supplementary motor area, the amygdala, the basal ganglia and even the cerebellum. In this study participants self-rated their own metacognition by a way of objective assessment. The scope of this study is to identify neural structures that are involved in the process of mental effort evaluation.

Historical section and limitations

The brain first started to be considered the seat of the mind in the 5th century BC by Alcmaeon of Croton in Magna Grecia (Adelman, 2009). Aristoteles who lived in the 3rd century BC opposed this idea as he believed the heart to be the seat of intelligence. He thought the brain to serve only as a cooling agent of the blood (Rolls, 2006). Claudius Galen who was born during the times of the Roman Empire in Pergamum (modern-day Turkey) by Greek parents, proposed that the seat of the rational soul was in the brain and believed that the rational soul controlled higher level cognitive functioning like decision making or information gathering from the environment and sending those signals to the brain, which worked by movement of animal spirits through the ventricles (Hankinson, 1991). He also listed imagination, memory, recollection, knowledge, thought, consideration, voluntary motion and sensation as being found within the rational soul (Hankinson, 1991). A universal cultural setback followed the fall of the Roman Empire lasting about 11 centuries. During the Renaissance Western European philosophers continued the works of ancient Greek philosophers. For example, Rene Descartes to add to Galen's theory suggested that the pineal gland was the seat of the soul and he thought of it as a canal transmitting animal spirits from the blood into the brain (Lokhorst, 2005).

An important breakthrough in the philosophy of mind was done in the 19th century by an American philosopher and psychologist named William James. In his work "The Principles of Psychology" (1890) he developed his theory of emotion. He suggested that a stimulus causes a physical response, and an emotion is just the consequence of this bodily experience and not the cause of the experience itself. For him, emotion was the mind's perception of physiological conditions. For example, the mind's perception of an increased adrenaline level and an elevated heartbeat can be regarded as the emotion of fear. His theory of emotion will be one of the foundation stones of this research because in some sense it shares much in common with the concept of interoception. Interoception can be defined as the sense of inner body experience and can be used as a guiding tool by an individual who is asked to rate different experiences on a given scale.

An important historical advance from psychology towards neuropsychology was first made by the German physician Franz Joseph Gall who developed the pseudoscience of phrenology in 1796. He developed this discipline based on the assumption that character, thoughts, and emotions can be found in specific brain areas. On the one hand, his theory has since been disposed by the scientific community but on the other hand it had opened the horizons for serious scientific study considering the brain as an organ comprised of different domains with different functions assigned to each domain rather than as a whole.

The first steps in development of functional neuroimaging were made by Angelo Mosso (1846–1910). He first developed the 'Mosso method' which consisted of measuring changes in cerebral blood flow in patients by recording brain pulsations (Sandrone et al., 2012). He noticed that when the experimental participants were engaged in tasks such as mathematical calculations (Berlucchi, 2009) the pulsations of their brains increased. This evidence led him to infer that brain activity was accompanied by an increase of blood flow. However, recording of brain pulsations had limitations, such as the impossibility of recording them non-invasively. Mosso tried to overcome this problem by building the "human circulation balance" (Sandrone et al., 2012). By positioning individuals in equilibrium during resting conditions he was able to study blood flow variations occurring during emotional or intellectual tasks. This revolutionary balance can be regarded as the first non-invasive "neuroimaging" technique (Sandrone et al., 2012).

An fMRI scanner cannot provide an ideal environment with the proper conditions for solving mathematical problems. This was the main reason that the design of the tasks was made in the format of multiple-choice questions. One of the attributes of such a format is to indirectly lead participants to use problem solving strategies such as approximations, exclusion method and guessing. As a result, the complexity created using several different strategies in solving one single task might affect the clear judgment of participants when asked to evaluate their own effort on solving the task.

Methods

Participants were right-handed people with no expertise in mathematics (e.g., a degree in mathematics) and no counterindications with fMRI who can easily follow instructions, focus on the tasks and perform them in a brief period. To test for counterindications participants were asked to fill a screening form and sign a consent form. Twenty healthy adults (10 females, 20 to 30 years old) participated in the fMRI study. Participants solved mathematical problems (addition, subtraction, multiplication, and division) in three levels of difficulty that were indexed by inclusion of 1-digit, 2-digit, and 3-digit numbers. They were asked to provide an answer to as many trials as they could during a time block of 32 seconds. There was a total of 36 math blocks of varying difficulty level. After each block participants were given 5 seconds to evaluate the difficulty of the current set; this is the metacognition event that occurred after every block of trials that lasted 32 seconds. A fixation interval of 10 seconds was used and three numerical tasks that did not involve mathematical operations were used as control blocks.

One group analysis examined metacognition in terms of difficulty level. It's main categories are metacognition task versus fixation, metacognition task versus operation task of control, metacognition task versus operation task of addition, metacognition task versus metacognition task of control and difficulty level > 1 (for all mathematical operations and the control task) versus difficulty level = 1 (for all mathematical operations and the control task). All categories in this group of contrast were FDR corrected using False Discovery Rate (FDR) using a *p*-value of 0.05 and also cluster corrected using 125 voxels. Clusters that survived the correction have their faces or edges touched, they are separated if the voxels have different signs and have 125 or more voxels.

The second group analysis examined metacognition in terms of operation. It's main categories are metacognition task versus fixation, metacognition task versus operation task of control, metacognition task versus operation task of addition and metacognition task versus metacognition task of control. All categories in this group of contrast were FDR corrected using a *p*-value threshold of 0.01 and also cluster corrected using AFNI's 3dClusterize command. Clusters that survived the correction have their faces or edges touched, they are separated if the voxels have different signs and have 30 or more voxels.

Results

Metacognition by difficulty. The results of the analysis examined metacognition in terms of difficulty level are presented in the Table 1 and Figure 1.

Metacognition by operation. The results of the analysis examined metacognition in terms of operation are presented in the Table 2 and Figure 2.

Table 1

Selection of the biggest clusters (in respect to cluster size) for each mathematical operation and the control task that appeared during the group analysis stage in terms of difficulty

MT vs FX	MT vs FTC	MT vs OTA	MT vs MTC
Right Declive	Left Middle Frontal Gyrus	Right Fusiform Gyrus	Left Precuneus
Right Insula	Left Posterior Cingulate	Right Caudate	Left Inferior Frontal Gyrus
Left Medial Frontal	Left Middle Frontal Gyrus	Right Middle Frontal Gyrus	Right Precuneus

Note. Results were FDR corrected for $p < 0.05$ and cluster corrected for 125 voxels. MT – metacognition task; FX – fixation; FTC – font task of control level 1; OTA – operation task of addition level 1; MTC – metacognition task of control level 1

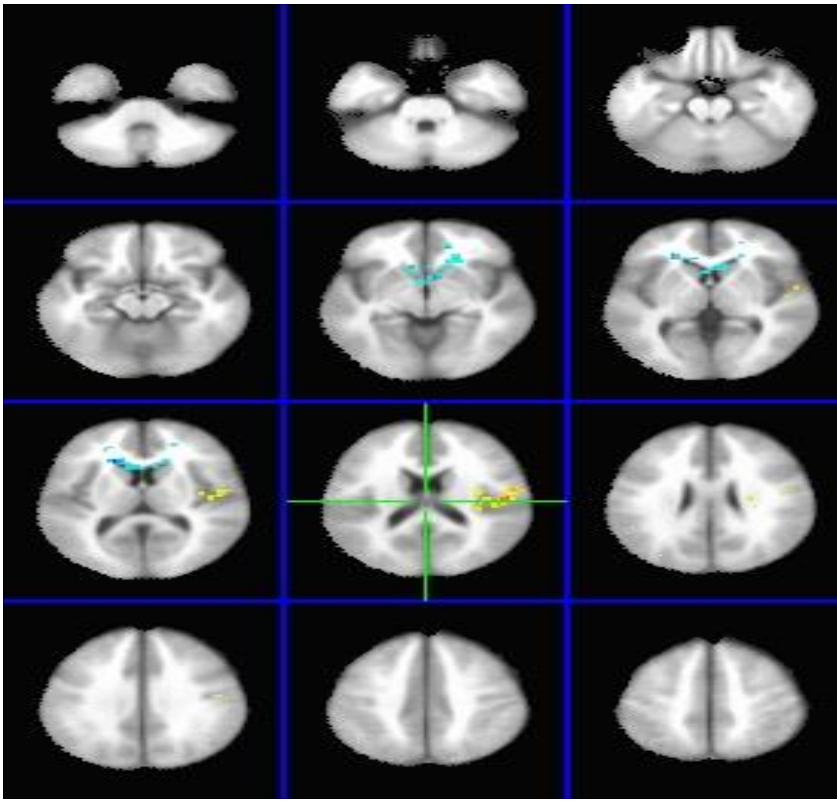

Figure 1. Clusters representation for the contrast division difficulty level 2 minus fixation

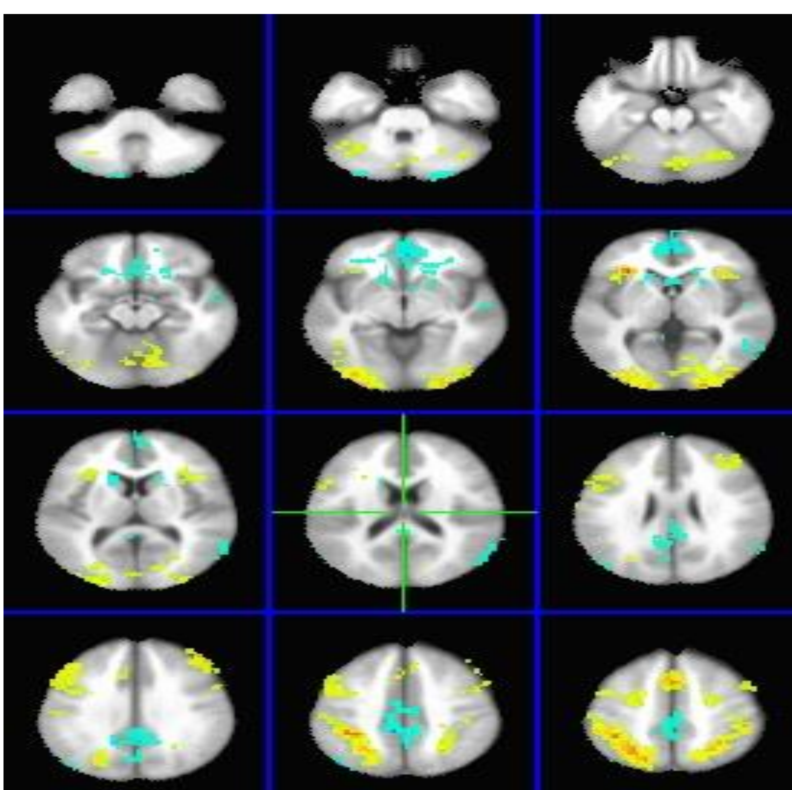

Figure 2. Clusters representation for the contrast metacognition task of addition minus control task

Table 2

Selection of the biggest clusters (in respect to cluster size) for each mathematical operation and the control task that appeared during the group analysis stage in terms of operation

Addition	Subtraction	Multiplication	Division	Control
Right Superio Parietal Lobule	Left Inferior Occipital Gyrus	Left Precuneus	Left Superior Frontal Gyrus	Right Middle Occipital Gyrus
Left Inferior Occipital Gyrus	Right Middle Occipital Gyrus	Right Superior Frontal Gyrus	Left Precuneus	Left Declive
Left Superior Frontal Gyrus	Right Superior Frontal Gyrus	Right Precentral Gyrus	Left Medial Frontal Gyrus	Left Precuneus
Left Inferior Parietal Lobule	Left Inferior Parietal Lobule	Right Cingulate Gyrus	Left Superior Frontal Gyrus	Right Middle Frontal Gyrus
Right Superior Parietal Lobule	Left Anterior Cingulate	Left Inferior Parietal Lobule	Left Inferior Parietal Lobule	Left Inferior Parietal Lobule
Left Cingulate Gyrus	Left Middle Frontal Gyrus	Left Medial Frontal Gyrus	Left Medial Frontal Gyrus	Left Fusiform Gyrus
Left Caudate	Right Lentiform Nucleus	Right Medial Frontal Gyrus	Left Anterior Cingulate	Left Declive
Left Precuneus	Left Precuneus	Right Paracentral Lobule	Left Inferior Parietal Lobule	Right Inferior Occipital Gyrus
Left Inferior Parietal Lobule	Left Middle Frontal Gyrus	Left Inferior Parietal Lobule	N/A	Left Superior Parietal Lobule

Note. Results were FDR corrected for $p < 0.01$ and cluster corrected for 30 voxels.

Discussion

Brain signal elicited during a metacognition task associated with mental effort to mathematical operations of three difficulty levels was examined. Results show a dynamic relation among metacognition, mathematical operation, and difficulty level. The following results are highlighted: (a) increases in task difficulty showed activations of the frontal lobe as well as cingulate and insular cortex areas (b) regarding metacognition in terms of mathematical operations, for addition high degree of activation was observed mainly in the parietal cortex, whereas for subtraction in the prefrontal cortex. The medial frontal gyrus seemed to be mostly active for both multiplication and division. Brain areas that were found to be active in all 4 mathematical operations were the parietal lobule, the precuneus and the cingulate gyrus. Results are discussed by focusing on metacognition and it's possible mechanisms of action.

Increases in task difficulty for the metacognition from level one to levels two and three (see Table 1) showed significant activations of brain areas frequently associated with metacognition such as the left and right middle frontal gyrus, left inferior frontal gyrus, left and right precuneus, right insula and left posterior cingulate. The anterior cingulate cortex seems to play a critical role in cognitive attention during the activation of the salience network of the brain (Sridharan et al., 2008) and has been marked with prevalent clusters in children's mathematical problem-solving (Arsalidou et al., 2018). In this part of the study which had to do with cognitive effort, the left posterior cingulate was found to be active.

In terms of metacognition by mathematical operations (see Table 2), for addition high volume and frequency of activation was observed in the right posterior parietal lobule, for subtraction in the left middle frontal gyrus, for multiplication the left and right medial frontal gyrus and precentral areas of the frontal lobe such as the right precentral gyrus and the right paracentral lobule, for division the left medial frontal gyrus and the left superior frontal gyrus and in the case of the control task no specific area seemed to be distinguishable from other areas. Furthermore, high volume and frequency of activation was observed in the left inferior parietal lobule for all operations but with less frequency in the cases of subtraction and the control task. Also, highly activated but with lesser frequency than the parietal lobule was found to be the left precuneus in all operations plus the control task and the left cingulate gyrus for all operations but not the control task. An attempt can be made to compare these results with the findings of a meta-analysis of brain areas needed for calculations (Arsalidou, Taylor, 2011). The current study found the superior/inferior parietal lobule to be active for addition but not the posterior parietal lobule. For subtraction the right middle/inferior frontal gyri were found to be a lot more active than the left middle frontal gyrus. For multiplication the left and right middle/inferior frontal gyri were found to be a lot more active than the left and right medial frontal gyrus. Also, precentral areas of the frontal lobe were not found to be active for multiplication. In the case of division there was no data due to lack of studies associated with the mathematical operation of division. Also, in addition and multiplication the left superior parietal lobule was found to be intensely active but that was not the case in subtraction were the left inferior parietal lobule predominated. These findings, when compared with the findings in this study, are suggesting adjacent brain areas (superior/middle/inferior) being involved in the system of mathematical cognition-metacognition problem solving. A shifting of left/right hemisphere system is also a possible mechanism involved.

Conclusion

The current research was focused on the contribution of various brain areas on metacognition related to mathematical operations. Although a relation exists between mathematical performance and metacognition, the semantic nature of this relation is poorly understood. The fMRI results in this study are shedding more light on the relation between mathematical performance and the cognitive process of metacognition. Finally, a strategic plan was made for future research. Future steps include a region of interest analysis and functional connectivity analyses of the insular with other math-related brain regions. Also dividing the participants in small groups based on their accuracy and reaction times and conducting several group analyses instead of just a single one, can be useful in better deciphering brain-behavior correlates providing insight especially for the harder levels of difficultly (levels 2 and 3). Additionally, correlating individual signal change and individual task performance will allow explaining with more confidence several anomalies that occasionally show up in the results.

References

Adelman, G. (2009). *Encyclopedia of neuroscience* (M. D. Binder, N. Hirokawa & U. Windhorst, Eds.). Berlin: Springer; Heidelberg. https://doi.org/10.1007/978-3-540-29678-2

Arsalidou, M., & Taylor, M.J. (2011). Is 2 + 2 = 4? Meta-analyses of brain areas needed for numbers and calculations. *NeuroImage*, *54*(3), 2382–2393. https://doi.org/10.1016/j.neuroimage.2010.10.009

Arsalidou, M., Pawliw-Levac, M., Sadeghi, M., & Pascual-Leone, J. (2018). Brain areas associated with numbers and calculations in children: Meta-analyses of fMRI studies. *Developmental Cognitive Neuroscience*, *30*, 239–250. https://doi.org/10.1016/j.dcn.2017.08.002

Baird, B., Cieslak, M., Smallwood, J., Grafton, S.T., & Schooler, J.W. (2015). Regional white matter variation associated with domain-specific metacognitive accuracy. *Journal of Cognitive Neuroscience*, *27*(3), 440–452. https://doi.org/10.1162/jocn_a_00741

Baird, B., Smallwood, J., Gorgolewski, K.J., & Margulies, D.S. (2013). Medial and lateral networks in anterior prefrontal cortex support metacognitive ability for memory and perception. *The Journal of Neuroscience*, *33*(42), 16657–16665. https://doi.org/10.1523/JNEUROSCI.0786-13.2013

Berlucchi, G. (2009). Chapter 13: The contributions of neurophysiology to clinical neurology: An exercise in contemporary history. In S. Finger, F. Boller & K. Tyler (Eds.), *History of Neurology* (vol. 95, pp. 169-188). Elsevier Science. https://doi.org/10.1016/S0072-9752(08)02113-1

Chua, E.F., Schacter, D.L., Rand-Giovannetti, E., & Sperling, R.A. (2006). Understanding metamemory: Neural correlates of the cognitive process and subjective level of confidence in recognition memory. *NeuroImage*, *29*(4), 1150–1160. https://doi.org/10.1016/j.neuroimage.2005.09.058

D'Argembeau, A., Ruby, P., Collette, F., Degueldre, C., Balteau, E., Luxen, A., Maquet, P., & Salmon, E. (2007). Distinct regions of the medial prefrontal cortex are associated with self-referential processing and perspective taking. *Journal of Cognitive Neuroscience*, *19*(6), 935–944. https://doi.org/10.1162/jocn.2007.19.6.935

Fechir, M., Gamer, M., Blasius, I., Bauermann, T., Breimhorst, M., Schlindwein, P., Schlereth, T., & Birklein, F. (2010). Functional imaging of sympathetic activation during mental stress. *NeuroImage*, *50*(2), 847–854. https://doi.org/10.1016/j.neuroimage.2009.12.004

Fleming, S. M., & Dolan, R. J. (2012). The neural basis of metacognitive ability. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1594), 1338–1349. https://doi.org/10.1098/rstb.2011.0417

Fleming, S. M., & Lau, H. C. (2014). How to measure metacognition. *Frontiers in Human Neuroscience*, *8*, 443. https://doi.org/10.3389/fnhum.2014.00443

Hankinson, R.J. (1991). Galen's anatomy of the soul. *Phronesis*, *36*(2), 197–233. https://doi.org/10.1163/156852891321052787

Lokhorst, G.-J. (2005). *Descartes and the pineal gland*. Retrieved April 20, 2023, from https://plato.stanford.edu/archives/win2021/entries/pineal-gland

Morales, J., Lau, H., & Fleming, S.M. (2018). Domain-general and domain-specific patterns of activity supporting metacognition in human prefrontal cortex. *The Journal of Neuroscience*, *38*(14), 3534–3546. https://doi.org/10.1523/JNEUROSCI.2360-17.2018

Rolls, E.T. (2006). Brain mechanisms of emotion and decision-making. *International Congress Series*, *1291*, 3–13. https://doi.org/10.1016/j.ics.2005.12.079

Sandrone, S., Bacigaluppi, M., Galloni, M.R., & Martino, G. (2012). Angelo Mosso (1846–1910). *Journal of Neurology*, *259*(11), 2513–2514. https://doi.org/10.1007/s00415-012-6632-1

Sedikides, C. (1993). Assessment, enhancement, and verification determinants of the self-evaluation process. *Journal of Personality and Social Psychology*, *65*(2), 317–338. https://doi.org/10.1037/0022-3514.65.2.317

Spalletta, G., Piras, F., Piras, F., Caltagirone, C., & Orfei, M. D. (2014). The structural neuroanatomy of metacognitive insight in schizophrenia and its psychopathological and neuropsychological correlates. *Human Brain Mapping*, *35*(9), 4729–4740. https://doi.org/10.1002/hbm.22507

Sridharan, D., Levitin, D.J., & Menon, V. (2008). A critical role for the right fronto-insular cortex in switching between central-executive and default-mode networks. *Proceedings of the National Academy of Sciences*, *105*(34), 12569–12574. https://doi.org/10.1073/pnas.0800005105

Sweller, J. (1988). Cognitive load during problem solving: effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4

Van der Meer, L., de Vos, A.E., Stiekema, A.P.M., Pijnenborg, G.H.M., van Tol, M.-J., Nolen, W.A., David, A.S., & Aleman, A. (2013). Insight in schizophrenia: Involvement of self-reflection networks? *Schizophrenia Bulletin*, *39*(6), 1288–1295. https://doi.org/10.1093/schbul/sbs122

Article history:
Received 12 May 2023
Revised 17 July 2023
Accepted 19 July 2023

For citation:
Kouzalis, A. (2023). A group level analysis of self-evaluations associated with cognitive load. *RUDN Journal of Psychology and Pedagogics, 20*(3), 578–587. http://doi.org/10.22363/2313-1683-2023-20-3-578-587

Conflicts of interest:
The author declares that there is no conflict of interest.

Bio note:
Alexios Kouzalis is a doctoral student of the Doctoral School of Psychology, HSE University (Moscow, Russia). He is a member of the Mathematical Cognition and Learning Society. ORCID: 0000-0002-0986-7896; Scopus Author ID: 57223436261; e-LIBRARY SPIN-code: 8038-5980. E-mail: alexiskouzalis@gmail.com

DOI: 10.22363/2313-1683-2023-20-3-578-587
EDN: AJYYHJ
УДК 159.91

Исследовательская статья

Групповой анализ самооценок, связанных с когнитивной нагрузкой

А. Кузалис

Национальный исследовательский университет «Высшая школа экономики», *Российская Федерация, Москва, 101100, ул. Мясницкая, д. 20*
alexiskouzalis@gmail.com

Аннотация. Самооценка – это процесс, посредством которого люди оценивают себя с целью улучшения некоторых аспектов своей личности или навыков, тесно связанный с когнитивной функцией метапознания. Цель исследования – изучение степени вовлеченности различных областей головного мозга в метапознание, поскольку оно связано с субъективными оценками когнитивных усилий при решении математических задач различной сложности. Для этого участникам эксперимента было предложено решить математические задачи (сложение, вычитание, умножение и деление) трех уровней сложности, находясь внутри сканера фМРТ. После решения каждой задачи они оценивали количество усилий, затраченных на ее решение. Во время получения ответов фиксировались сигналы мозга, которые затем анализировались с помощью специальных компьютерных программ. Результаты показали, что увеличение сложности задачи активирует лобную долю, поясную и островковую области коры головного мозга. Обнаружено, что теменная долька, предклинье и поясная извилина также активируются во время всех четырех математических операций.

Ключевые слова: когнитивная нагрузка, самооценка, нейровизуализация, групповой анализ

Благодарности и финансирование. Исследование проведено при поддержке Российского научного фонда (грант № 17-18-01047) и Российского фонда фундаментальных исследований (грант № 19-313-51010).

История статьи:
Поступила в редакцию 12 мая 2023 г.
Принята к печати 19 июля 2023 г.

Для цитирования:
Kouzalis A. A group level analysis of self-evaluations associated with cognitive load // Вестник Российского университета дружбы народов. Серия: Психология и педагогика. 2023. Т. 20. № 3. С. 578–587. http://doi.org/10.22363/2313-1683-2023-20-3-578-587

Заявление о конфликте интересов:
Автор заявляет об отсутствии конфликта интересов.

Сведения об авторе:
Кузалис Алексиос, аспирант, Аспирантская школа по психологии, Национальный исследовательский университет «Высшая школа экономики» (Москва, Россия). Член международной научно-профессиональной организации «Математическое познание и обучающееся общество». ORCID: 0000-0002-0986-7896; Scopus Author ID: 57223436261; e-LIBRARY SPIN-код: 8038-5980. E-mail: alexiskouzalis@gmail.com