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An Understanding of (Mis)Understanders: Exploring the Underlying Mechanisms of Concept Learning Using Functional Magnetic Resonance Imaging

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ABSTRACT— Obtaining adequate understanding of scientific concepts is considered challenging due to learners' misconceptions about natural phenomena. Misconceptions may coexist with scientific knowledge in the brain. Therefore, misconceptions must be cognitively inhibited in order to select the scientific knowledge. There is, however, lack of substantial neuroscientific evidence supporting this hypothesis. In this study, we sought for this evidence by investigating medical students who solved a cardiovascular conceptual problem in a magnetic resonance imaging scanner. Brain activation was compared between understanders who had the scientific knowledge, and misunderstanders who held a misconception. No significant activation was found in brain areas related to cognitive inhibition in understanders compared with misunderstanders. Therefore, we could not confirm the idea that cognitive inhibition is involved in overcoming a misconception. Instead, we found that the putamen was significantly activated in misunderstanders compared with understanders, suggesting a role for episodic memory in learners holding a misconception.

Learning scientific concepts can be challenging due to the prevalence of misconceptions. Misconceptions are conceptions that are inconsistent with scientific knowledge, resulting in inaccurate conceptual understanding (Chi, Slotta, & De Leeuw, 1994; Potvin, 2013). Notably, misconceptions tend to be very robust and often persist after formal education (Palizvan, Nejad, Jand, & Rafeie, 2013; Periago & Bohigas, 2005). In order to help educators design effective teaching and learning strategies to alleviate misconceptions, we aim to understand the underlying mechanism of concept learning.

Different theoretical frameworks attempt to delineate the learning pathway from misconception to scientific conception, also referred to as conceptual change (Duit & Treagust, 2012). A hypothesis is that initial misconceptions are never fully removed after conceptual change, but that they coexist with the scientific conception (Potvin, 2013, 2017; Shtulman & Lombrozo, 2016). This implies that one may choose the conception with a higher cognitive utility in the context of interest, a process called 'competitive evaluation' (Ohlsson, 2009).

Competitive evaluation implies that the misconception should be suppressed, i.e. inhibited. Cognitive inhibition is defined as the stopping or overriding of a mental process, in whole or in part, with or without intention (MacLeod, 2007). Behavioral studies have investigated reaction time as an indicator of activation of inhibitory processes. When given limited time to answer a question, students and even expert scientists tended to endorse teleological explanations of

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natural phenomena (Kelemen & Rosset, 2009; Kelemen, Rottman, & Seston, 2013; Shtulman & Valcarcel, 2012). The rationale behind these experiments is that one's ability to inhibit misconceptions is impaired by processing demands. Thus, misconceptions about natural phenomena may possibly never be removed from the brain, and therefore need to be cognitively inhibited when one wants to reason in a scientifically correct way. Various behavioral studies support this statement by linking inhibition ability or executive functioning to conceptual learning in various natural sciences including mathematics and physics (Butterfuss & Kendeou, 2020; Cragg & Gilmore, 2014; Mason, Zaccoletti, Carretti, Scrimin, & Diakidoy, 2019; Vosniadou et al., 2015). However, there is lack of substantial evidence from cognitive neuroscience that supports the hypothesis about the role of cognitive inhibition in conceptual understanding.

Cognitive inhibition seems related to activation in specific brain areas, including the anterior cingulate cortex (ACC), anterior insula, dorsolateral prefrontal cortex (dlPFC), and parietal regions (Hung, Gaillard, Yarmak, & Arsalidou, 2018). However, most functional magnetic resonance imaging (fMRI) studies were unable to show significant (Family Wise Error corrected) activation in these areas in 'understanders' who, according to the hypothesis, inhibit their misconception compared with 'misunderstanders', who hold the misconception (Dunbar, Fugelsang, & Stein, 2007; Foisy, Potvin, Riopel, & Masson, 2015; Fugelsang & Dunbar, 2005; Masson, Potvin, Riopel, & Foisy, 2014; Vaughn, Brown, & Johnson, 2020). Consequently, no study has yet confirmed the hypothesis that misconceptions are never removed from the brain and need to be inhibited when one has to provide the scientific knowledge.

Our study explores which brain areas are involved in (mis)understanding scientific concepts. More specifically, we investigate the idea that cognitive inhibition is involved in suppressing misconceptions in understanders. Therefore, our research question is: Do understanders show more activation in brain areas related to cognitive inhibition compared with misunderstanders? Our findings will provide insight in the brain areas associated with concept learning and may have implications for educational practice regarding teaching scientific concepts.

METHODS

Participants

Fifty undergraduate students voluntarily participated in this study, who studied medicine, biomedical sciences or clinical technology at the Leiden University Medical Center.

To avoid potential priming effects, students were not subjected to any questionnaires prior to the fMRI experiment.

No abnormal neurological history was reported by the participants and they all had normal or corrected-to-normal vision. Only right-handed students were included. Written informed consent was obtained with approval from the Leiden University Medical Center Institutional Ethical Review Board (P19.027).

fMRI Task

The fMRI task included movies illustrating a common misconception in physiology, which entails that the velocity of blood decreases when it enters a constricted section of a vessel, just like cars slow down when the road narrows (Figure 1). This reasoning is incorrect because blood, being a liquid, cannot be compressed and will not slow down when it enters a constricted section of a vessel. Rather, the conservation of mass law implies that a reduction in cross-sectional area goes with an increase in blood velocity, i.e. the scientific conception. This misconception about blood velocity has been demonstrated previously among both students and teachers (Sungur, Tekkaya, & Geban, 2001; Yip, 1998). All participants had direct instruction about this concept during their education.

During the fMRI task, four types of movies were presented: (1) misconception movies showed blood flowing slower through a narrowed part of a vessel, (2) scientific movies showed blood flowing faster through a narrowed part of a vessel, (3) positive control movies showed a vessel without narrowing in which blood velocity did not change, (4) negative control movies showed a vessel without narrowing in which blood velocity would suddenly change. Blood velocity was illustrated by showing a single moving blood cell moving through the vessel.

All conditions included a vessel, but the vessel's location was different for each movie so participants had to stay focused. Furthermore, the direction of the blood cell's movement varied from left to right and from right to left. In the scientific condition and misconception condition, blood velocity could increase or decrease at the vessel narrowing. In the control conditions, the speed could increase, decrease, or remain unchanged because no vessel narrowing was present in these conditions.

The stimuli were pseudo-randomly presented in an event-related design. The movies lasted 4.0 s each, followed by a jittered interstimulus interval of 3.0–5.0 s. In total, 82 stimuli were presented: misconception $N = 21$, scientific conception $N = 21$, negative control $N = 20$, positive control $N = 20$. The stimuli were divided into two runs of 41 stimuli each, resulting in a total time of 5 min 27 s per run. Participants had a short break in the scanner in-between runs.

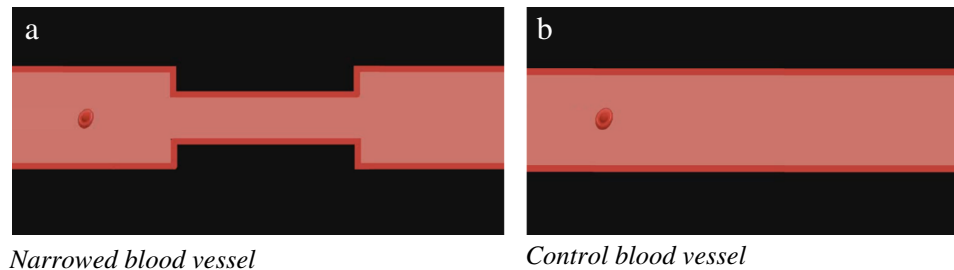


Fig. 1. Examples of stimuli presented in the MRI scanner during the blood velocity task: (a) Narrowed blood vessel used in the misconception condition and scientific conditions, (b) Control blood vessel used in the negative control condition and positive control conditions.

Procedure

Participants received oral instructions from the first author MV prior to the experiment. They were informed about the various task conditions that would be presented in the scanner and asked to press the left (correct) or right (incorrect) button after each movie. They watched one example movie of each condition outside the scanner.

Stimuli were presented using E-Prime 2.0 software (Psychology Software Tools, Inc.) via a BOLD screen LCD for fMRI (Cambridge Research Systems), which could be seen by using the mirror located in the head coil. Responses were collected with an MRI-compatible button response box (correct: left button with index finger, incorrect: right button with middle finger). Participants were explicitly informed not to move during scanning.

After scanning, participants were taken back to the interview room and performed a short post-test. To confirm their behavioral results in the MRI scanner, they were asked to give a written response to the question: “What happens to the velocity of the blood cell in the narrowed part of the vessel compared to its velocity before the narrowing?”. Additionally, participants provided a confidence score regarding their answer on a 5-point Likert scale (complete guess, rather unsure, doubting, almost sure, completely sure).

Group Classification

Based on the fMRI task responses and post-test answers, participants were classified as understanders or misunderstanders. Understanders were participants who provided 90% or more correct answers to the scientific and misconception stimuli. Misunderstanders answered incorrectly to at least 90% of scientific and misconception stimuli. Participants who failed to meet these criteria were excluded from the analysis ($n = 3$).

Image Acquisition and Preprocessing

MRI data were acquired with a Philips 3.0 Tesla MRI scanner (Ingenia, Philips Medical Systems, Best, the

Netherlands) using a standard 32-channel head coil. For registration purposes, a three-dimensional T1-weighted structural image was acquired prior to the functional images. Structural images were obtained with TR/TE = 7.9/3.5 ms, flip angle = 8°, FOV = 250 × 195 mm, voxel size = 1.10 × 1.10 × 1.10 mm, number of slices = 155. Functional images were obtained with two runs using a gradient echo EPI sequence: TR/TE = 2,200 / 30 ms, flip angle = 80°, FOV = 220 × 220 mm, and voxel size = 2.75 × 2.75 × 2.75 mm, number of slices = 153.

Preprocessing was performed using FSL libraries (FSL 5.0.11, Oxford, United Kingdom, www.fmrib.ox.ac.uk/fsl) (Smith et al., 2004). Non-brain tissue was removed from the structural images using a semi-automated brain extraction tool as implemented in FSL (Smith, 2002). Functional images were high-pass temporally filtered (100 s), motion corrected using MCFLIRT, and spatially smoothed by using a 6-mm Gaussian kernel. Functional images were registered to the corresponding T1-weighted images using Boundary-Based Registration. T1-weighted images were registered to the 2 mm isotropic MNI152 standard space image using nonlinear registration with a warp resolution of 10 mm. All scans were submitted to a visual quality control check before and after preprocessing to ensure that no gross artifacts were present in the data.

Data Analyses

Stimulus timing files were created for each participant based on the movie onset times plus reaction time. To model the time course of the BOLD signal, a general linear model was used for the within- and between-subject analyses (Woolrich, Behrens, Beckmann, Jenkinson, & Smith, 2004), convolved with a hemodynamic response function. Temporal derivatives of the convolved regressors were included in the statistical design to account for potential offsets in peak BOLD responses. In addition, six movement parameters were included in the model as regressors of no interest, to account for differences in movement, even after motion correction. Gender was included as a covariate.

Table 1
Group Descriptives

		Understanders (n = 20)	Misunderstanders (n = 27)
Age		20.35 (1.87)	20.96 (1.58)
Gender	Male	5	0
	Female	15	27
Major	Medicine	8	19
	Biomedicine	6	5
	Clinical technology	6	3
Accuracy	Misconception	20.95 (0.22)	0.11 (0.32)
	Scientific conception	20.60 (1.00)	0.26 (0.53)
	Negative control	19.90 (0.45)	20.00 (0.00)
	Positive control	19.70 (0.92)	19.74 (0.66)
Confidence		3.80 (1.01)	4.04 (0.59)

FSL FMRI Expert Analysis Tool (FEAT) was used for the MRI data analyses (Smith et al., 2004). A first-level analysis within subjects was used to obtain an independent outcome for each contrast on a single-subject basis. A second-level analysis was performed to concatenate the two sessions per subject (fixed effects). A third-level group analysis was performed to obtain the contrasts of interest on a group level (random effects, 5,000 permutations, unpaired t-test). Group-level activation maps were created using a cluster defining threshold of $p < .001$ and a cluster extent threshold of $p < .05$ (FWE corrected).

Participants' demographics and response accuracy were analyzed using independent Students t-tests. Reaction times were analyzed using a generalized estimating equations model, including groups, stimuli and groups*stimuli as factors and reaction time as an independent variable (IBM SPSS Statistics Version 23.0, IBM Corp. Armonk, NY, USA).

RESULTS

Group Characteristics

Based on their response pattern, participants were classified as either understanders or misunderstanders, resulting in two groups (Table 1). Response accuracy was significantly different between groups for the misconception, $t(45) = -249.16$, $p < .001$, $d = 75.89$, and scientific conception, $t(45) = -90.73$, ($p < .001$), $d = 25.42$, but not for the negative control, $t(45) = 1.17$, $p = .25$, $d = 0.31$, and positive control, $t(45) = 1.78$, $p = .41$, $d = 0.05$.

There was no significant difference in the 5-point Likert confidence scores of the understanders (3.80 ± 1.01) compared with the misunderstanders (4.04 ± 0.59), $t(45) = 1.22$, $n = 47$, $p = .32$, $d = 1.16$.

Overall, understanders responded slower than misunderstanders in all four conditions ($B = 0.96$, $SD = 0.44$, $p = .03$) (Table 2). Within each group, there were no significant differences in reaction times between the different conditions.

Table 2

Reaction Times (sec) of Understanders and Misunderstanders for the Four Different Conditions

Condition	Understanders (n = 20) Reaction Time M (SD)	Misunderstanders (n = 27) Reaction Time M (SD)
Misconception	2.52 (0.14)	2.41 (0.15)
Scientific	2.51 (0.15)	2.41 (0.16)
Negative control	2.49 (0.13)	2.40 (0.15)
Positive control	2.57 (0.16)	2.43 (0.17)

Neuroimaging Data

Figure 2 shows the brain areas that were significantly activated in understanders (Figure 2a) and misunderstanders (Figure 2b). Furthermore, the comparisons between these two groups are shown in Figure 2c,d. Details on cluster activation can be found in Table S2.

Understanders

Within the understanders group, activations were found for all four conditions in superior- and inferior parietal areas (BA7, BA39, BA40), temporal areas (BA22, BA37, BA41), inferior prefrontal cortex (BA44), supplementary motor area (SMA, BA6), insula (BA13) putamen (BA49), and ACC related areas (BA24, BA32) (Figure 2a). Additionally, activation of the anterior prefrontal cortex (BA10) and ventrolateral prefrontal cortex (vlPFC, BA47) was shown for the misconception and negative control condition.

Misunderstanders

Misunderstanders showed activation in brain areas similar to the understanders in all conditions. These include superior and inferior parietal areas (BA7, BA39, BA40), inferior prefrontal cortex (BA44), temporal areas (BA22, BA37, BA41), SMA (BA6), insula (BA13) putamen (BA49), and

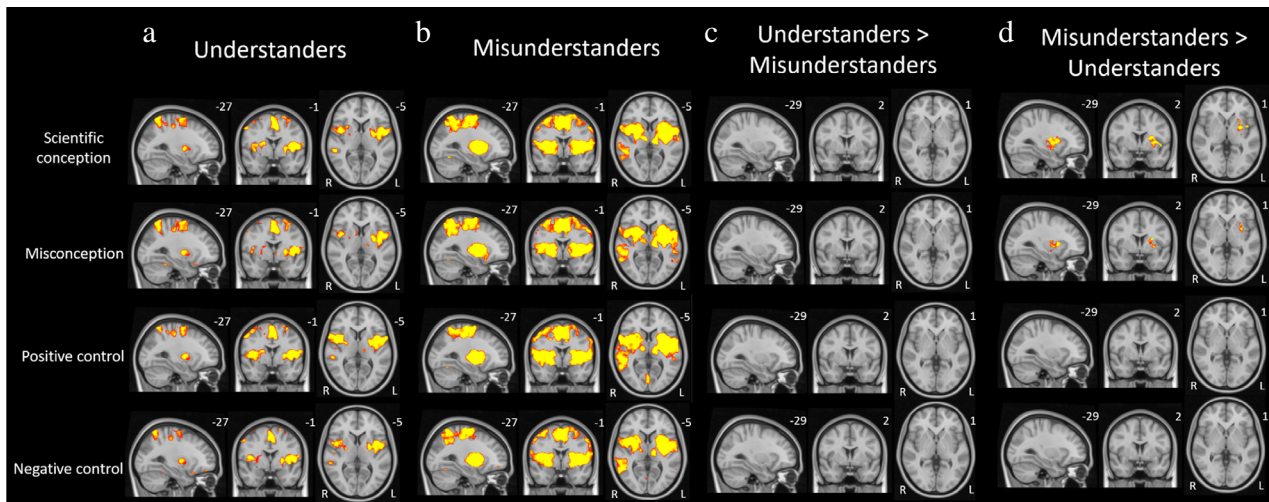


Fig. 2. Brain areas activated during the four conditions in understanders, misunderstanders, and in the comparison between both groups. (a) Understanders showed significant activation in parietal and temporal areas, inferior prefrontal cortex, SMA, insula, putamen, and the upper part of the ACC in all four conditions. Only for the misconception and negative control, significant activation was shown in the anterior- and vPFC. (b) Misunderstanders showed significant activation in parietal and temporal areas, inferior prefrontal cortex, dlPFC, SMA, insula, putamen, and the upper part of the ACC in all conditions. Additionally, significant prefrontal activation in the anterior prefrontal cortex was found in the negative control only. (c) In none of the conditions, understanders showed more brain activity compared with the misunderstanders. (d) In both the scientific condition and misconception condition, the putamen was more activated in the misunderstanders compared with the understanders. All findings were cluster-defining thresholded $p < .001$, cluster extent thresholded $p < .05$, FWE corrected, using random effect analysis.

ACC related areas (BA24, BA32) (Figure 2b). Contrary to the findings in understanders, activation was also found in the dlPFC (BA9) in all conditions. Additional prefrontal cortex activation (BA8, BA10) was found in the negative control condition.

Misunderstanders Compared with Understanders

Misunderstanders showed more brain activation in the putamen (BA49) compared with the understanders for the scientific conception and misconception condition (Figure 2d). For the positive and negative control, there were no significant differences between groups (Figure 2c,d). The understanders did not show more brain activity compared with the misunderstanders as none of the relative activations survived the $p < .05$ threshold (Figure 2c).

Comparison of Different Conditions

Figure 3 shows brain areas that were significantly activated in comparisons between different conditions. Results are displayed for understanders (Figure 3, left column) and misunderstanders (Figure 3, right column) separately. Details on cluster activation can be found in Table S3.

For the scientific conception and misconception, there was more brain activity compared with the control conditions in parietal regions (BA7, BA39, BA40) in both groups (Figure 3a–d). Additionally, for misunderstanders, more

brain activity was found in the visual association region (BA18) and occipito-temporal cortex (BA19) in all comparisons except for the scientific conception versus positive control (Figure 3b–d). Furthermore, misunderstanders showed more activation in the fusiform gyrus (BA37) for the misconception versus positive control (Figure 3c).

In the negative control condition compared with the positive control condition, more brain activity was found in parietal areas (BA39, BA40) in both groups (Figure 3e). Additionally, misunderstanders showed more brain activity in the superior parietal lobe (BA7), whereas understanders showed more activity in temporal regions (BA21, BA37, BA38).

Prefrontal brain areas displayed more brain activity in two comparisons. This finding was limited to understanders only. First, in the misconception compared with positive control, more brain activity was found in the orbitofrontal cortex (BA11) and vPFC (BA47) (Figure 3c). Similarly, more brain activity was found for the negative control compared with the positive control, with additional greater activation in the anterior prefrontal cortex (BA10) (Figure 3e).

In the scientific conception compared with the misconception, greater activation was found in visual associative areas (BA18), the angular gyrus (BA39) and temporal regions (BA21, BA37), for misunderstanders only (Figure 3f). Understanders showed no greater relative activation for this comparison.

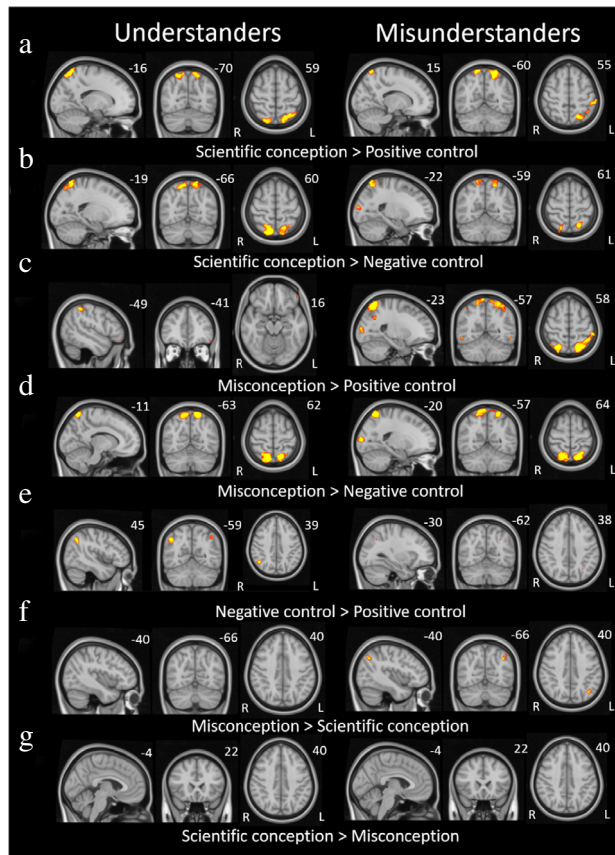


Fig. 3. Comparison of the different conditions in understanders and misunderstanders. (a) In the scientific conception compared with the positive control condition, more brain activity was found in parietal regions in both groups. (b) In the scientific conception compared with the negative control condition, more brain activity was found in parietal areas, visual associative areas, and the occipito-temporal cortex in both groups. (c) In the misconception compared with the positive control condition, more brain activity was found in parietal areas and prefrontal areas in understanders. For misunderstanders, more brain activity was found in parietal areas, temporal areas, and visual-associative areas. (d) In the misconception compared with the negative control condition, more brain activity was found in parietal areas in understanders. For misunderstanders, additional greater activation was found in visual associative areas and the occipito-temporal cortex. (e) In the negative control condition compared with the positive control condition, greater activation was found in parietal areas, temporal areas, and prefrontal areas in understanders. For misunderstanders, greater activation was found only in parietal areas and the occipito-temporal cortex. (f) In the misconception compared with the scientific conception condition, no significant activation was found for the understanders. For misunderstanders, greater activation was found in parietal areas, visual associative areas, and temporal areas. (g) In the scientific conception compared with the misconception, no significant activation was found in both groups. All findings were cluster-defining thresholded $p < .001$, cluster extent thresholded $p < .05$, FWE corrected, using random effect analysis.

DISCUSSION

The present study investigated underlying mechanisms of concept learning by comparing brain activity in understanders and misunderstanders. The hypothesis that understanders cognitively inhibit their misconception could not be confirmed by our findings. Instead, brain activity was found in brain areas related to cognitive inhibition in both groups and in control conditions. We suggest that this activation may reflect memory retrieval rather than cognitive inhibition. In addition to previous studies, we report greater activation in the putamen in misunderstanders, suggesting a role of episodic memory in learners holding a misconception.

A Role for Cognitive Inhibition?

Our findings showed brain activity in areas associated with cognitive inhibition including the dorsal ACC, dlPFC, vlPFC, SMA, parietal lobe regions, insula, and putamen (Hung et al., 2018). However, understanders did not show more activation in these areas compared to misunderstanders. Moreover, these areas were also more activated in the positive control condition, which makes their contribution to cognitive inhibition in this task questionable (Nenciovici et al., 2018). Rather, our findings seem in line with a behavioral study that was unable to show a link between inhibitory processes and mathematics achievement (Ng, Lee, & Khng, 2017).

Furthermore, reaction times were slower in understanders compared to misunderstanders. This may indicate activation of inhibitory processes, however, understanders were also slower in control conditions. Therefore, a more suitable explanation may be that the cognitive load in understanders was increased during the experiment, a finding which requires further investigation. In all, we are unable to support the cognitive inhibition hypothesis that was posed by previous researchers (Foisy et al., 2015; Masson et al., 2014; Vaughn et al., 2020).

The Dorsal ACC

Researchers have suggested that the ACC can trigger an inhibition response when it detects a cognitive conflict between two coexisting representations (Masson et al., 2014; Vaughn et al., 2020). The ACC activity in our study, however, may rather represent monitoring of ongoing behavior or guidance of decision-making (Botvinick, 2007) activation was found in all conditions, including the positive control where no conflicting information is presented. Another explanation could be that ACC activation found in this study represents surprise signaling, because stimuli were presented in a pseudo-random order (Vassena, Deraeve, & Alexander, 2020) or that ACC activation is merely a reflection of the attentive state of our participants during the experiment.

Because it has been stated ironically that the ACC is involved in almost everything, researchers should be cautious with interpreting ACC activation (Vassena, Holroyd, & Alexander, 2017).

The Bilateral vLPFC and dLPFC

The vLPFC (BA47) has also been linked to cognitive inhibition (Allaire-Duquette, Bélanger, Grabner, Koschutnig, & Masson, 2019; Foisy et al., 2015). In line with previous findings, we found vLPFC activation in understanders while viewing the misconception. However, vLPFC activity was also present in the negative control condition. Additionally, we found inferior frontal gyrus/vLPFC (BA44) activity in all conditions, suggesting that the role of the vLPFC in overcoming a misconception is questionable and warrants further research.

Hung and colleagues showed that vLPFC activation is mainly associated with response inhibition instead of cognitive inhibition (Hung et al., 2018), which implies a response inhibition task (e.g. Go/No go) may be used as an additional control in experimental designs that aim to uncover the role of vLPFC in science learning.

A Role for Memory Processes?

The dLPFC activity found in our study among misunderstanders was present in all conditions and could be linked to memory processes rather than cognitive inhibition (Brunoni & Vanderhasselt, 2014). Similarly, ventrolateral prefrontal areas have been linked to memory retrieval by previous studies (Kim, 2010; Spaniol et al., 2009).

In addition to prefrontal areas, increased activation in parietal lobe areas was found in all conditions. These regions could also reflect memory retrieval (Cabeza, 2008; Cavanna & Trimble, 2006; Spaniol et al., 2009). A previous study on conceptual change by Nenciovici and colleagues showed activation in parietal lobe areas and related this to memory retrieval mechanisms, specifically episodic recollection (Cabeza, 2008; Nenciovici et al., 2018; Spaniol et al., 2009). Additionally, functional network studies in patients have also found the insula to be related to episodic memory processing (Xie et al., 2012). Furthermore, the fusiform gyrus which was active in almost all conditions has previously been associated with memory processing (Daniel, Katz, & Robinson, 2016) and the SMA has been linked to working memory function (Cañas, Juncadella, Lau, Gabarrós, & Hernández, 2018). Note that none of these regions was more activated in the understanders compared with the misunderstanders or vice versa, meaning that putative memory processing was induced by the task in all participants irrespective of the group they were in.

A Role for the Putamen?

The only region that was found more activated in misunderstanders compared to understanders was the putamen. Putamen activity was found in experimental conditions specifically, so we can rule out that this activity was due to a motor response. Potentially, its activation reflects cognitive mechanisms as it has been shown in previous research, that the putamen is involved in learning and memory (Ell, Helie, Hutchinson, Costa, & Villalba, 2011).

The putamen appears to be associated with stimulus encoding and maintenance with its activity increasing in a cognitive load-dependent manner (Cairo, Liddle, Woodward, & Ngan, 2004; Chang, Crottaz-Herbette, & Menon, 2007). Misunderstanders may experience enhanced cognitive load compared to understanders. Because understanders could have automated their scientific response pattern to the point that the contribution of working memory has been reduced. Interestingly, however, understanders had slightly longer reaction times than misunderstanders for all conditions, which questions the idea of reduced working memory and more automated processing among understanders.

Putamen activity has also been linked to episodic memory processes as several studies have showed that increased activity in the putamen during encoding predicts subsequent retrieval success (Ell et al., 2011; Sadeh, Shohamy, Levy, Reggev, & Maril, 2011; Ystad, Eichele, Lundervold, & Lundervold, 2010). Following this line of reasoning, misunderstanders may make more use of their episodic memory while viewing scientific movies and misconception movies. Perhaps this is a result of misunderstanders addressing prior naïve beliefs in order to respond to scientific and misconception stimuli. It should be noted that the putamen has been shown to be more active for semantic than perceptual episodic memory tasks (Prince, Daselaar, & Cabeza, 2005).

Implications for Science Education

It is a long way from brain imaging to the development of instructional designs for education (Howard-Jones et al., 2016). Still, our findings may provide directions for teaching scientific concepts. Based on putamen activity and activation of other brain areas related to episodic memory, we support the crucial role of prior knowledge in teaching scientific concepts (Hewson & Hewson, 1983). If no correct or coherent long-term memory is available to provide anchorages for new scientific ideas, this may distort the learning process as it becomes difficult for learners to construct meaning out of new information (Johnstone, 1991). Instruction regarding conceptual understanding of scientific concepts should aim to disclose students' prior knowledge and assumptions about the concept of interest. Additionally,

explicit attention to metacognitive components of learning may also facilitate the putative control processes that are involved in concept learning (Allaire-Duquette et al., 2019; Bartley et al., 2019).

Limitations

We were unable to select participants based on their prior knowledge (e.g. having correct knowledge or a misconception), as has been done in other studies (Foisy et al., 2015; Masson et al., 2014). We did not include such a pre-test in our study design as we believe this would harm the validity of the experiment by evoking priming effects. Instead of a pre-test, we used a post-test after the MRI scan to determine if a participant held a misconception. By analyzing the answers on the post-test we could confirm that all participants who answered incorrectly in the scanner did indeed hold the misconception.

We cannot confirm if the understanders have had a misconception initially, e.g. prior to the physiology course. It was assumed that all participants held or have had the misconception, based on literature and personal teaching experiences (Sungur et al., 2001; Yip, 1998). The lack of insight in students' development of knowledge over their life course, including potentially debunking misconceptions, has also been an issue in previous research (Foisy et al., 2015; Masson et al., 2014) and should be taken into account in future studies.

This study examined a single misconception which may impact its generalizability, because different misconceptions may show variations in their scientific nature. However, examining a single misconception allowed us to limited potential confounders such as cognitive load processes and thought processes related to these different natures.

Cluster extent based thresholding is accompanied with low spatial specificity, which makes it difficult to make inferences about the statistical significance of specific locations within the cluster. Despite the low spatial specificity, this method of analysis allowed us to minimize the number of false positive findings.

CONCLUSION

A hypothesis derived from science education research states that activation of inhibitory processes is needed to overcome misconceptions that reside in the brain. The present study could not confirm this hypothesis. Instead, findings suggest a role for episodic memory in learners holding a misconception based on greater activation in the putamen. This supports the idea that educators should be aware of the crucial role of prior knowledge when teaching scientific concepts.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1: Supplementary Information

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