At the heart of learning: navigating towards educational neuroscience in health professions education

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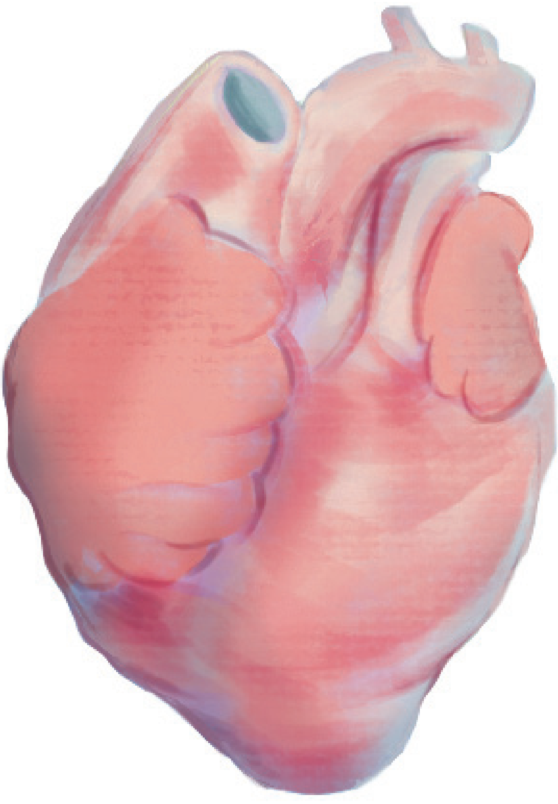

An understanding of (mis)understanders: exploring the underlying mechanisms of concept learning using functional magnetic resonance imaging

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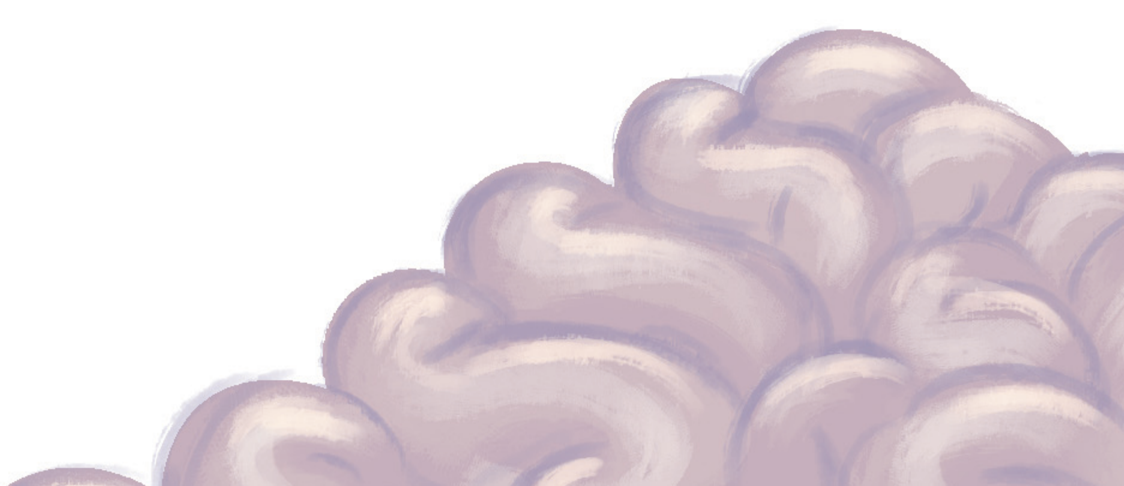

Abstract

Obtaining adequate understanding of scientific concepts is considered challenging due to learners' erroneous 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.

Introduction

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 et al., 1994a; Potvin, 2013). A learner holding a misconception is referred to as a 'misunderstander', whilst a leaner with the correct scientific conception is an 'understander'. Notably, misconceptions tend to be very robust and often persist after formal education (Palizvan et al., 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). The idea that a misconception can coexist with scientific knowledge implies that one should be able to select the scientific knowledge over the misconception. This process has been referred to as 'competitive evaluation', in which the conception with a higher cognitive utility in the context of interest is chosen (Ohlsson, 2009).

Behavioural experiments imply that competitive evaluation requires cognitive inhibition (Hung et al., 2007). This finding was based on studying reaction time as an indicator of activation of inhibitory processes. For instance, when given limited time to answer a question, students and even expert scientists tended to endorse teleological explanations of natural phenomena (Kelemen & Rosset, 2009; Kelemen et al., 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. 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 et al., 2018). However, current 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 et al., 2007; Foisy et al., 2015; Fugelsang & Dunbar, 2005; Masson et al., 2014; Vaughn et al., 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 aims to investigate which brain areas are involved in (mis) understanding scientific concepts. Therefore, we test the hypothesis whether 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 therefore have implications for educational practice regarding teaching scientific concepts.

Methods

Participants

Fifty health professions education students participated in this study. These participants were undergraduates at the Leiden University Medical Center studying medicine, biomedical sciences or clinical technology. The participants were enrolled in physiology courses during their education which were all organised by the same coordinator (PS). In these courses, all students were taught about the physiological concept of blood velocity that was underlying the fMRI task.

Students could sign up for the experiment voluntarily. In order to avoid potential priming effects, the students were not subjected to any tests or questionnaires prior to the fMRI experiment. Consequently, it was unknown if the participant was holding the misconception or not prior to the fMRI scan.

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

fMRI task

For the fMRI task, we used movies illustrating a common misconception in medical physiology, which entails that students believe 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 thought is incorrect since 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. All students had direct instruction about this concept during their medical training.

During the task, participants were asked to determine if movies on blood velocity were correct or incorrect by pressing one of the two buttons with the index finger or middle finger, respectively. Four different conditions were presented using four types of movies: (1) misconception movies showed the incorrect conception that blood flows slower through a narrowed part of a vessel, (2) scientific movies showed the correct scientific conception that blood flows faster through a narrowed part of a vessel, (3) positive control movies showed a vessel without narrowing in which the velocity of the blood did not change, (4) negative control movies showed a vessel without narrowing in which the speed of the blood would suddenly change. The blood velocity was illustrated by showing a single moving blood cell moving through the center of the vessel.

A participant was classified as an understander when he/she responded correctly to both the misconception and the scientific conception condition, or as a misunderstander when he/she responded incorrectly to these conditions during the fMRI task. Understanders and misunderstanders were expected to respond similarly to the positive and negative control conditions. These conditions were used to ensure that the task was understood correctly by all participants. Additionally, the negative control could potentially involve inhibition related to error-detection whereas the positive control was expected not to trigger any inhibitory mechanisms. All conditions included a vessel, but the location of the vessel was different in each movie to ensure that participants had to stay focused. Furthermore, the direction of the blood cell's movement varied from left to right and from right to left.

The stimuli were randomly presented according to an event-related design, in which the same condition never occurred twice in a row. The movies lasted 4.0 sec each. Each movie was followed by a fixation cross for 3.0-5.0 sec. In total, 82 stimuli were presented: misconception condition n = 21, scientific condition n = 21, negative control condition n = 20, positive control condition n = 20. The stimuli were divided into two runs of 41 stimuli each, resulting in a total time of 5 min 27 sec per run. The participants were given a short break in the scanner in-between the two runs.

Procedure

Participants were given oral instructions by the first author (MV) and watched one example movie of each condition outside the scanner. Next, participants were placed into the MRI scanner for the data acquisition. During the task, 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. Participants' responses (correct or incorrect) were collected with an MRI-compatible button response box. Participants were explicitly informed not to move during scanning.

After the scan session, participants were taken back to the interview room and performed a short post-test. To confirm their behavioural 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, the 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 their behavioural data during the fMRI task and their answer given on the written post-test, participants were classified as understanders or misunderstanders respectively. The understanders were participants who held the scientific conception that "blood flows faster through a narrowed part of a vessel". During the fMRI task, participants needed to provide 90% or more correct answers to the scientific stimuli and misconception stimuli in order to be classified as an understander. The misunderstanders were participants who held the misconception that "blood flows slower through a narrowed part of a vessel". During the fMRI task, participants needed to answer incorrectly to the scientific stimuli and misconception stimuli for more than 90% to be classified as a misunderstander. Participants who tended to be misunderstanders, but who had more than 10% correct answers for scientific stimuli and misconception stimuli were excluded from the analysis (n = 2). One participant had more than 10% missing answers and was also excluded from the analysis.

Image acquisition and preprocessing

The MRI data was acquired with a Philips 3.0 Tesla MRI scanner (Ingenia, Philips Medical Systems, Best, the Netherlands) using a standard 32-channel head coil.

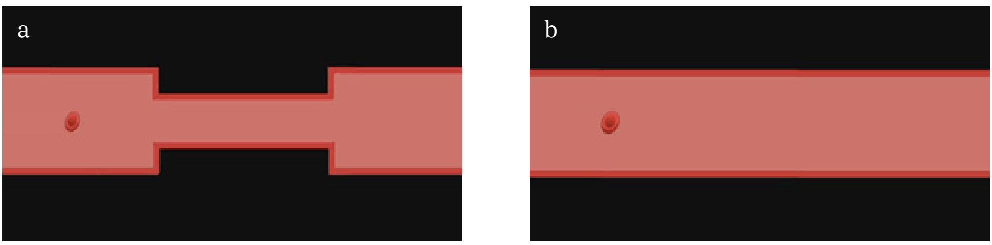

Figure 1 | Examples of stimuli presented in the MRI scanner during the blood velocity task: (a) Narrowed blood vessel used in the misconception condition and scientific conditions, (b) Control blood vessel used in the negative control condition and positive control conditions.

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 x 195 mm, voxel size = 1.10 x 1.10 x 1.10 mm, number of slices = 155. Functional images were obtained with two runs using a gradient echo EPI sequence: TR/TE = 2200 / 30 ms, flip angle = 80˚, FOV = 220 x 220 mm, and voxel size = 2.75 x 2.75 x 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). First, non-brain tissue was removed from the structural images using a semi-automated brain extraction tool as implemented in FSL (Smith, 2002). Next, functional images were high-pass temporally filtered (100 sec), 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 artefacts were present in the data.

Data analyses

Stimulus timing files were created for each participant based on the movie onset times and stimulus duration (= movie onset time + 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 et al., 2004). The model was 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.

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, 5000 permutations, unpaired t-test). Group-level activation maps were created using a cluster defining threshold of $p < .001$ and a cluster extent threshold of $p < .05$ (Family Wise Error (FWE) corrected).

Participants' demographics and behavioural data were analysed using independent Students t-tests (IBM SPSS Statistics Version 23.0, IBM Corp. Armonk, NY, USA).

Results

Group characteristics and behavioural data

Participants were divided in two groups: understanders (n = 20, age: 20.4±1.9, gender: 25% male) and misunderstanders (n = 27, age: 21.0±1.6 (p = .230), gender: 0% male (p = .005)). These two groups were based on the following behavioural data: understanders answered correctly to the misconception (21 out of 21) and scientific conception (20.6 out of 21), misunderstanders answered incorrectly to the misconception (0.1 out of 21) and the scientific conception (0.3 out of 21). Both groups answered correctly to the positive control (understanders: 19.7, misunderstanders: 19.7 out of 20) and the negative control condition (understanders: 19.9, misunderstanders: 20.0 out of 20). The difference in response accuracy was significant between the groups for the misconception (p < .001) and the scientific conception (p < .001), but not for the control conditions. These results were fully consisted with participants' written answers on the post-test (not shown).

To verify that participants were confident in their given answer, they reported their confidence after the task on a 5-point Likert scale. There was no significant difference in the 5-point Likert confidence scores of the understanders (3.8±1.0) compared with the misunderstanders (4.0±0.6), p = .320.

Table 1 presents the reaction times of understanders and misunderstanders. Overall, understanders responded slower than misunderstanders in all four conditions. Within each group, there were no significant differences in reaction times between the different conditions.

Neuroimaging data

Figure 2 shows the brain areas that were significantly activated in understanders (Figure 2A) and misunderstanders (Figure 2B) when performing the blood velocity

Table 1 | 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)*	p
Misconception	2.52 (0.14)	2.41 (0.15)	.010
Scientific	2.51 (0.15)	2.41 (0.16)	.040
Negative control	2.49 (0.13)	2.40 (0.15)	.048
Positive control	2.57 (0.16)	2.43 (0.17)	.006

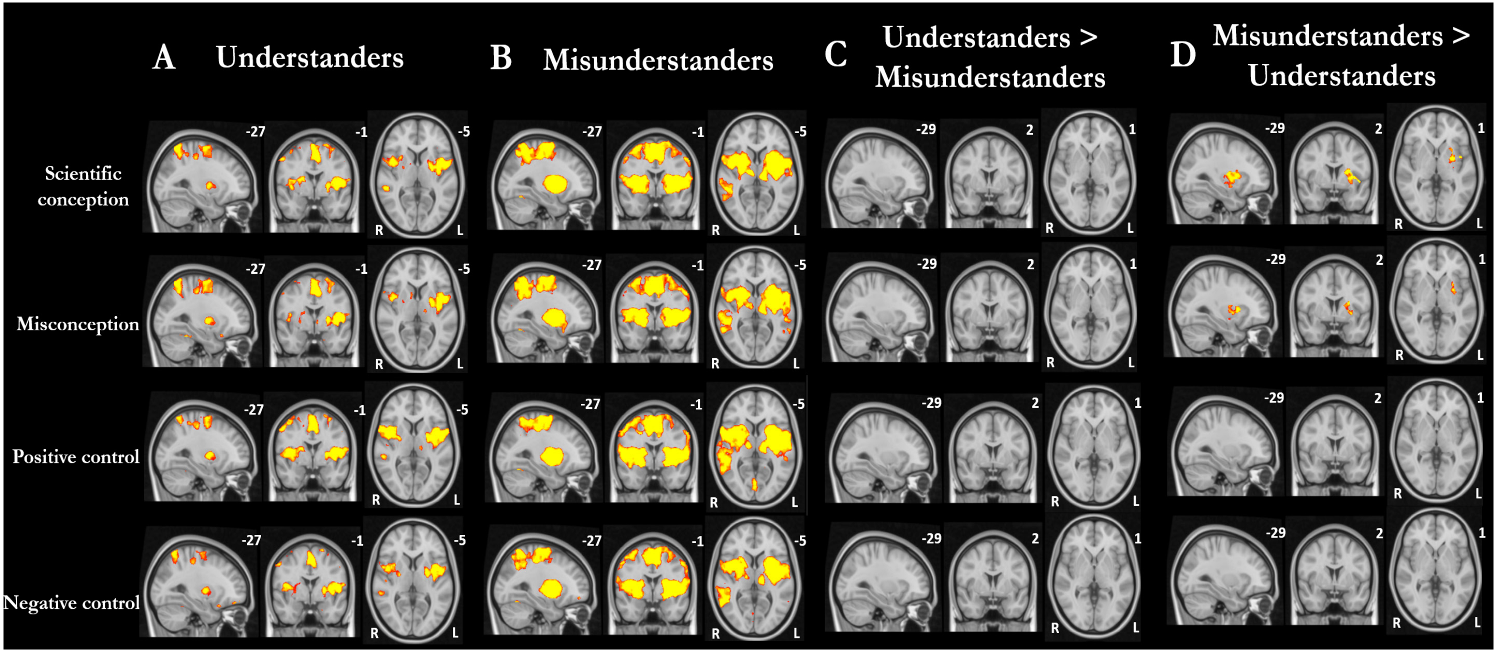

Figure 2 | Brain areas activated during the four conditions in understanders, misunderstanders, and in the comparison between both groups. A) Understanders showed significant activation in parietal and temporal areas, inferior prefrontal cortex, SMA, insula, putamen, and the upper part of the ACC in all four conditions. Only for the misconception and negative control, significant activation was shown in the anterior- and vlPFC. 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.

fMRI task. Furthermore, the comparisons between these two groups are shown (Figure 2C and 2D). Details on cluster activation can be found in Supplementary G.

Understanders

Within the understanders group, significant activations were found for all four conditions in superior- and inferior parietal areas (BA7, BA39, BA40), temporal areas (BA22, BA37, BA41), the inferior prefrontal cortex (BA44), the supplementary motor area (SMA, BA6), the insula (BA13) the putamen (BA49), and brain areas related to the ACC (BA24, BA32) (Figure 2A). Additionally, significant 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 significant activation in brain areas similar to the understanders in all conditions. These brain areas include the superior and inferior parietal areas (BA7, BA39, BA40), the inferior prefrontal cortex (BA44), temporal areas (BA22, BA37, BA41), the SMA (BA6), the insula (BA13) the putamen (BA49), and brain areas related to the ACC (BA24, BA32) (Figure 2B). Contrary to the findings in the understanders, significant 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 significantly 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 the groups (Figure 2C and 2D). 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

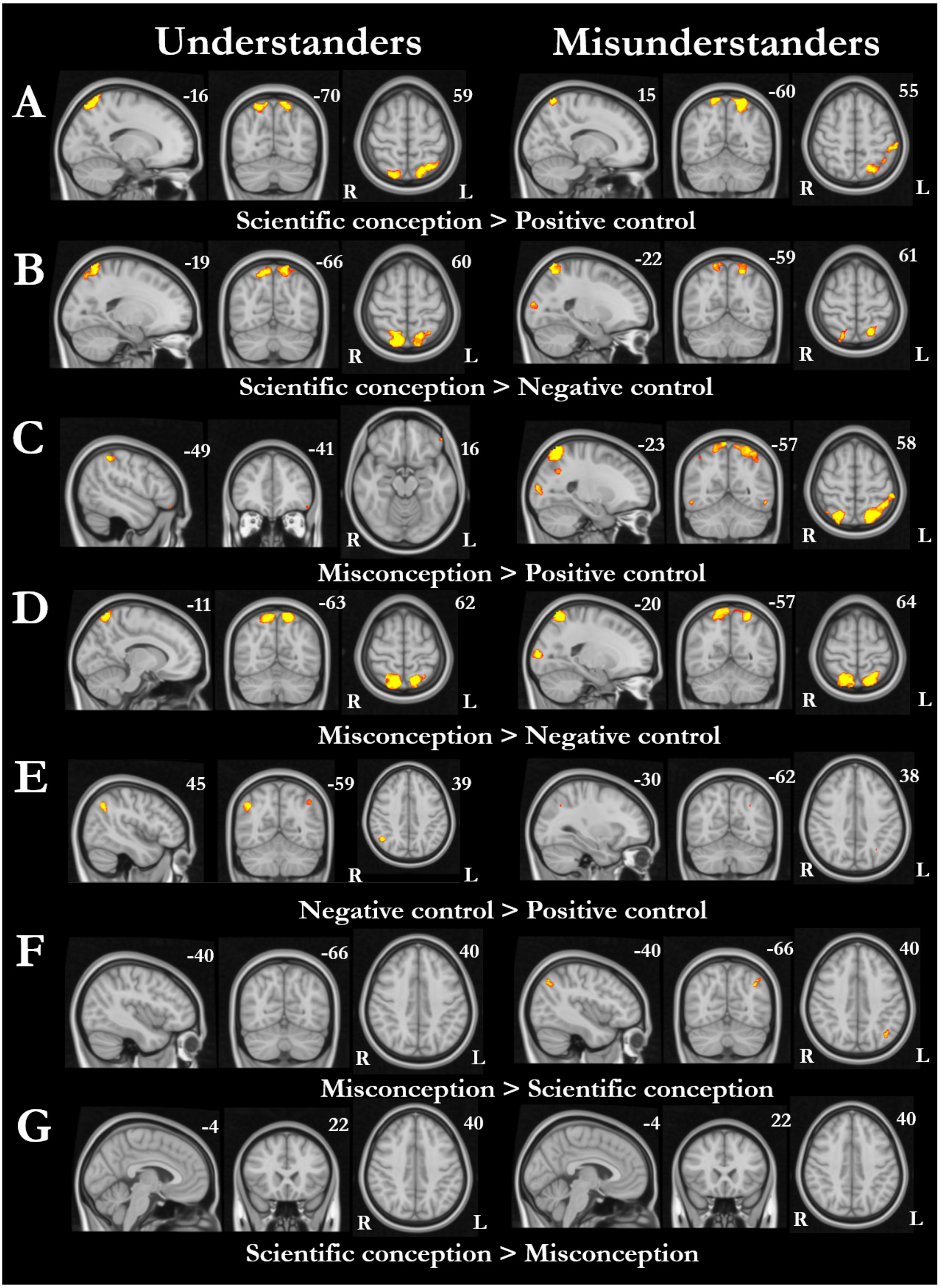

Figure 3 | Comparison of the different conditions in understanders and misunderstanders. A) In the scientific conception compared with the positive control condition, more brain activity was found in parietal regions in both groups. B) In the scientific conception compared with the negative control condition, 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.

cluster activation can be found in Supplementary H.

For both the scientific conception and misconception, there is 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, for misunderstanders, more brain activity was found for the superior parietal lobe (BA7). Understanders showed more brain activation 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 vlPFC (BA47) (Figure 3C). Similar, 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.

Discussion

The present study investigated the underlying mechanisms of concept learning by comparing brain activity in understanders and misunderstanders. The hypothesis that understanders cognitively inhibit their misconceptions could not be confirmed by our findings. Instead, we found brain activity in brain areas related to cognitive inhibition in both groups and also in control conditions. We suggest that these brain areas may play a role in 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 show more activation of brain areas that have been suggested to be associated with cognitive inhibition: the dorsal ACC (BA32), the bilateral dlPFC and vlPFC (BA9, BA44), SMA (BA6), parietal lobe regions (BA7, BA40), the insula (BA13), and the putamen (BA49) (Hung et al., 2018). However, understanders did not show more activation in brain areas related to cognitive inhibition compared with misunderstanders. Moreover, these brain areas are more activated for all conditions including the positive control condition. This makes the contribution of these brain areas to putative cognitive inhibition in this task questionable (Nenciovici et al., 2018). Consequently, 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

Previous studies have reported on the role of cognitive inhibition in overcoming misconceptions and linked this process partly to the ACC (Masson et al., 2014; Vaughn et al., 2020). According to these studies, the ACC triggers the inhibition response when it detects a cognitive conflict between two coexisting representations. Based on our results, however, we suggest that ACC activation rather represents the monitoring of ongoing behaviour or guidance of decision-making in general (Botvinick, 2007). Namely, the ACC is more activated in all conditions in our experiment, including the positive control where no conflicting information is presented.

The bilateral vlPFC and dlPFC

Another brain region that has been linked to the role of cognitive inhibition is the vlPFC (BA47, BA10) (Allaire-Duquette et al., 2019; Foisy et al., 2015). Researchers found more activation of this brain area in understanders compared with misunderstanders when viewing misconception movies, and propose that the vlPFC could be directly involved in the action of inhibition (Foisy et al., 2015). In line with previous findings, we found vlPFC activation in understanders when they viewed the misconception. In our case, however, the vlPFC was also more activated in the negative control condition. Additionally, we found activation of the inferior frontal gyrus/vlPFC (BA44) in all conditions. In sum, this suggests that the role of the vlPFC in overcoming a misconception is still questionable and warrants further research. Additionally, Hung and colleagues showed that vlPFC activation is mainly associated with response inhibition instead of cognitive inhibition (Hung et al., 2018), which implies that response inhibition task (e.g. Go/No go) may be used as an additional control in experimental designs that aim to uncover underlying mechanisms of science learning. A similar line of reasoning applies to the dlPFC (BA9), which has also been shown to be involved in multiple forms of inhibition (Hung et al., 2018).

A role for memory processes?

We found activation of the dlPFC (BA9) in the misunderstanders across all conditions. Instead of addressing this activation to inhibitory processes, we suggest that this activation could be linked to memory processes (Brunoni & Vanderhasselt, 2014). Similarly, ventrolateral prefrontal areas (e.g. BA10) have been linked to memory retrieval by previous studies (Kim, 2010; Spaniol et al., 2009).

In addition to the prefrontal areas, increased activation in the parietal lobe areas (BA7, BA39, BA40) was found in all conditions. These regions could also reflect memory retrieval rather than cognitive inhibition (Cabeza, 2008; Cavanna & Trimble, 2006; Spaniol et al., 2009). A previous study on conceptual change by Nenciovici and colleagues also showed activation in parietal lobe areas (BA7, BA39, BA40) 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 (BA13) to be related to episodic memory processing (Xie et al., 2012). Furthermore, the fusiform gyrus (BA37) which was active in almost all conditions has previously been associated with memory processing as well (Daniel et al., 2016) and the SMA (BA6) has been linked to working memory function (Ca□as et al., 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 (BA49). This region showed greater activation in the misunderstanders while scientific movies and misconception movies were presented. The putamen is involved in various types of motor behaviour. However, the brain activity was found in experimental conditions specifically, so we can rule out that this activity is related to a motor response. Potentially, the activation reflects cognitive mechanisms that are associated with the misconception movies and scientific movies. It has been shown in previous research, that the putamen is involved in learning and memory (Ell et al., 2011).

Neuroimaging studies have proposed that the putamen is associated with stimulus encoding and maintenance with its activity increasing in a cognitive load-dependent manner (Cairo et al., 2004; Chang et al., 2007). Therefore, misunderstanders may experience enhanced cognitive load when viewing scientific movies and misconception movies compared to understanders. An explanation could be that the understanders 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 efficient 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 et al., 2011; Ystad et al., 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 et al., 2005). In sum, further research needs to be conducted in order to clarify the role of the putamen in concept learning.

Implications for science education

It is a long way from brain imaging to the development of instructional designs for educational practice (Howard-Jones et al., 2016). Still, our findings may provide directions for teaching scientific concepts. Based on the putamen activity and the activation of other brain areas related to episodic memory during the fMRI task, we support previous recommendations that focus on the crucial role of prior knowledge in teaching scientific concepts (Hewson & Hewson, 1983). Instruction regarding conceptual understanding of scientific concepts should aim to disclose students' prior knowledge and assumptions about the concept of interest. Additionally, students' confidence in their prior knowledge may be addressed and students' awareness on the robustness of their misconceptions should be emphasised by educators. Although we did not find evidence for the role of cognitive inhibition in conceptual understanding, explicit attention to such 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

This study has several limitations. First, we were not sure 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 theory, but this could not be confirmed based on our study design as we did not want to induce any priming effects. The lack of insight in students' prior knowledge has also been an issue in previous research on this topic (Foisy et al., 2015; Masson et al., 2014) and should be taken into account in future studies. Second, 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 minimise the number of false positive findings. Lastly, only a small number of men participated in our study, which is possibly a consequence of the male:female ratio (1:3) in medical schools.

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 finding supports the idea that educators should be aware of the crucial role of prior knowledge when teaching scientific concepts.