The implementation of metacognitive strategies in pedagogy: supporting anatomical plasticity in the developing human brain

■ Michael Adjani

Introduction

The brain is the most complex organ in the human body; it acts as the command centre for every thought, function and behaviour, and provides sentience for all we know in everyday life. Using an educational-based biopsychosocial lens, Maslow's hierarchy of needs can be used to outline a set of cognitive capacities, including perception, intellect and learning as foundations that contribute to the wholeness of an individual (Maslow & Lewis, 1987).

Shifting toward a neuroanatomical focus, one of the key areas highlighting human cognitive growth is the emergence of metacognition. This presents itself during adolescence, typically between the ages of 8-10 (Whitebread & Neale, 2020), further developing into adulthood. Throughout this stage, the brain constructs neuronal circuits by forming newer synaptic connections, providing the ability to continuously learn and conceptualise stored information to respond to various stimuli from the environment. The formation and plasticity of such neuronal circuits (responsible for learning and memory) are fundamentally found in the temporal lobe, with a focus on the hippocampus (Yao *et al,* 2016).

The terms 'plasticity' or 'neuroplasticity' can be defined as the brain's ability to undergo temporary or permanent changes as a result of learning from its environment (Tovar-Moll & Lent, 2016). The process of neuroplasticity consists of a biological set of mechanisms that are responsible for the way the brain receives, encodes, stores and retrieves mutually exchanged information (Tovar-Moll & Lent, 2016). These highlighted factors are pertinent when looking into a higher cerebral function, such as problem-solving, in a metacognitive fashion. Metacognition or 'thinking about thinking' is a higher-order thinking process involving active control over cognitive capacities (Zemira & Bracha, 2014). Wholly, it is necessary that said processes particularly in the hippocampus are correctly stimulated to promote plasticity to improve an individual's metacognitive abilities.

Links to education policy

Throughout education policy, two factors that are emphasised are metacognition and student wellbeing (Sanger & Dorjee, 2016). The Department for Education (DFE) furthers this when elaborating on the importance of metacognition to be targeted in all aspects of curricula (DfE, 2022). A demand for research is therefore created in attempts to support evidence-based practice. Regarding the above, establishing the connection between neuroscience and pedagogy is crucial when drawing upon the link between neuroplasticity and metacognition. One could introduce the thought that increasing plasticity may contribute to increased cognitive development. This systematic scoping of literature draws upon various studies to include discussions on how current strategies in education support metacognition, the prevalence of neuroplasticity in education settings, and the relationship between metacognition and brain plasticity.

Methodology and procedures

This study describes phenomena in the context of science education, whilst aiming to pair cognitive science with teaching practice. The paper will avoid numerical expression due to its qualitative nature. The search purposes required the extracted literature to remain innovative, as this allows the induction of further research into the area of cognitive science and teaching. Literature searches were carried out using a variety of online databases and academic journals including, but not limited to, LibrarySearch, Science Direct and SpringerOpen. There remained a strict criterion regarding search terms, which allowed results to

be filtered toward the specific study area. The Boolean operator of 'AND' was used when searching various databases; using 'AND' provided more precise results and permitted the search of two phenomena concurrently. Search terms included a variation of 'metacognition AND education', 'plasticity AND the brain', and 'plasticity AND metacognition'. Papers included in this review were kept to 2010–present, except where sufficient evidence revealed a necessity to provide context, e.g. pedagogical practices still relevant today. Articles must have a focus on either adolescent and/or neural development, or learning theory and education. Excluded papers were considered as those that had a broad focus, no link to cognitive or neural development, and those whose referencing was deemed not to have considered international relevance. This paper carried out a thematic analysis, which supported the identification of patterns and associations throughout the given literature.

Developing metacognition

Focusing on the journey of cognition in a child's early years, developments in the ability to approach higher-order tasks as they age, is a prominent example of an adolescent's schema transitioning from the organisation of knowledge to meet basic psychological needs into achieving an essence of self-actualisation (Maslow & Lewis, 1987). Maslow and Lewis (1987) describe self-actualisation as a state of motivation whereby the brain requires little extrinsic intervention when approaching a problem-solving task. During this process, data stored throughout an individual's experience are retrieved from the hippocampus, which is met by input from the environment to inform decision-making (Palombo *et al,* 2015). The capability for an individual to generate a thought or course of action and then critique this decision in accordance with what they have learned is evidence for metacognition at work. An example in education can often be seen through questioning that can be described as an 'extended abstract'. With this, students can link several related ideas and build on this by making connections to bigger ideas and concepts within science. Six mark questions within summative assessments are examples of extended-abstract questioning, as students are prompted to give more comprehensive answers. These students would have the ability to hypothesise, design experiments to test said hypothesis (Biggs & Collis, 2014) and provide a critical conclusion. Biggs and Collis (2014) support this by suggesting that a student's quality of response is linked to developmental growth in their cognition. Noticeably, there is a correlation between increased data stored in the hippocampus and increased metacognition.

Related publications, however, place efforts in spatial thinking as the core driver of metacognitive growth. Ishikawa and Newcombe (2021) focus on STEM (science, technology, engineering and maths) learning to justify this. Teachers of STEM use an array of symbolic spatial tools, such as maps, graphs and diagrams, as powerful resources to enhance pupil reasoning. Educators see this as particularly beneficial in science (Ishikawa & Newcombe, 2021), as students are often required to apply a combination of skills, e.g. applied maths and task-recall, to coherently understand various phenomena. Pedagogical research discusses the use of spatial tools as having a significant benefit to students as they progress through to higher education. Flynn (2018) studied the impact of experiential-based learning tenanted to spatial learning, mentioning that the result when used effectively allows students to access all cognitive learning levels within Bloom's taxonomy (Bloom *et al,* 1956). Arguably, more current research alludes to favouring the use of 'SOLO' taxonomy over Bloom's, as SOLO targets the student's critical thinking skills specifically in understanding the concept of learning outcomes, which supports 21st century ideas of learning to solve real-life cognitive problems (Triana *et al,* 2023). Table 1 below outlines the basic features of SOLO taxonomy and provides more links between developmental age and the learning level of the student.

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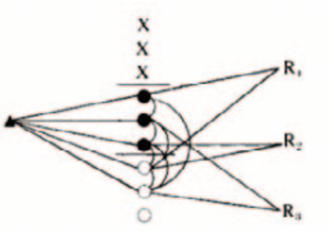
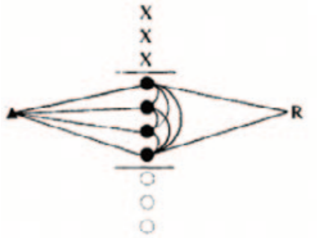
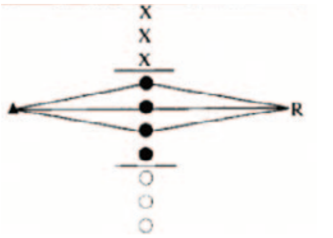
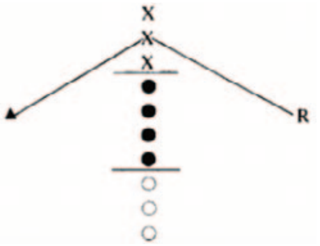
Table 1. Base stage of Cognitive Development and Response Description (Biggs & Collis, 2014).

Development base stage with minimal age	SOLO Description	1 Capacity	2 Relating operation	3 Consistency and Closure	4 Response Structure *Cue* *Response*
Formal Operations (16+ years)	Extended Abstract	*Maximal*: cue + relevant data + interrelations + hypothesis	Deduction and induction. Can generalise to situations not experienced	Inconsistencies resolved. No felt need to give closed decisions—conclusions held open, or qualified to allow logically possible alternatives. (R_1, R_2 or R_3)	
Concrete Generalisation (13-15 years)	Relational	*High*: cue + relevant data + interrelations	Induction. Can generalise with given or experienced context using related aspects	No inconsistency within the given system, but since closure is unique, inconsistencies may occur when he goes outside the system	
Middle Concrete (10-12 years)	Multistructural	*Medium*: cue + isolated relevant data	Can 'generalise' only in terms of a few limited and independent aspects	Although has a feeling for consistency, can be inconsistent because closes too soon on basis of isolated fixations on data, so can come to different conclusions with same data	
Early Concrete (7-9 years)	Unistructural	*Low*: cue + one relevant datum	Can 'generalise' only in terms of one aspect	No felt need for consistency, thus closes too quickly: jumps to conclusions on one aspect, and so can be very inconsistent	
Pre- Operational (4-6 years)	Prestructural	*Minimal*: cue and response confused	Denial, tautology, transduction. Bound to specifics.	No felt need for consistency. Closes without even seeing the problem	

[α] Kinds of data used: X = irrevelant or inappropriate; ● = related and given in display; ○ = related and hypothetical, not given.

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By addressing SOLO characteristics, including dimensions of capacity, the use of SOLO taxonomy can better facilitate learners in building a multi-structural response (Biggs & Collis, 2014). In fact, evidence supporting SOLO appears to have up-to-date pedagogical theory compared to Bloom's (mainly due to extensive research in this area), presenting itself as a more appropriate learning theory to take into consideration when discussing catalysts to cognitive growth, e.g. spatial learning. However, current evidence tying spatial learning to SOLO taxonomy with a neuroscientific lens is limited and so may benefit from further research before using this taxonomy specifically to promote spatial thinking.

Despite disparities among the leading channels to metacognition, stages in cognitive progression remain the same. Briefly focusing on the final stage of cognitive growth (Table 1) allows students to develop skills necessary for deduction and criticality, no longer needing to rely on external motivation to achieve self-autonomy (Maslow & Lewis, 1987). The Department for Education (DFE) provides statutory guidance for all education providers within the UK, which creates a baseline as to how best students can be supported in their learning. This includes producing independent and autonomous learners post-16 (DfE, 2022). In line with these requirements, Biggs and Collis (2014) state that, by the abstract stage, students have the ability to think with criticality. This can be visualised using a response structure (Table 1), where an individual identifies cues to generate several responses. The emphasis here is the rearrangement of information to generate a structured critical response with multiple outcomes. Subsequently, data from this framework can be used when factoring in key indicators of metacognitive ascension.

A brief understanding of neuronal networks

Over the course of human life, the brain continually reorganises itself based on input and exposure; an individual's home, school and social life all help to shape the neural circuits associated with the topic of plasticity (Sousa, 2016). Within this, there must be an importance stressed upon understanding dendritic and synaptic changes of neurons in brain maturation. Simplified, these synapses represent the basic cellular unit for memory. Poo *et al* (2016) elaborate on this, stating that long-term memory is stored in a set of spines, where these spines are persistently formed and modified during learning. In further support, empirical research evidences the accumulation of neural networks as building blocks for plastic processes, which are typical of neural development (Bonfanti & Charvet, 2021). Assuming that brain maturation corresponds to cognitive growth (from adolescence through to adulthood), the aforementioned collaboratively establishes the vitality for plasticity to be facilitated across educational settings.

Plasticity in the classroom

In accordance with DFE requirements, literacy and numerical abilities are traditionally emphasised in UK classrooms, particularly in STEM curricula (DfE, 2022). Nevertheless, recent evidence has introduced the important role and responsibilities of spatial learning in academic achievement. Ishikawa and Newcombe (2021) highlight mental rotation as a core characteristic in STEM learning; this is due to the skill having positive correlations with the successful completion of several other spatial thinking tasks within various cognitive challenges. Mental rotation refers to the process whereby the brain rotates mental representations of imaging, e.g. diagrams and animations. Within science education, students are often confronted with schematic diagrams, for instance when being taught the topic of electrical circuits. Students can then expect to be assessed on their ability to show an understanding of circuit drawings and answer questions displaying suitable rigour. The duty of mental rotation would be to allow the student to reimagine the electrical circuit and mentally manipulate its structure in the interest of the given question.

Indeed, this would be an unreasonable task for students who lack the cognitive aptitude to do so; in response, Ishikawa and Newcombe (2021) made reference to papers investigating the relationship between how the malleability of learning mechanisms in the brain inform mental rotation. The outcomes suggest that learners who struggle with mental rotation initially will require practice to utilise this skill effectively. The practice may include embedding mental rotation activities into classroom routines at specific times during the lesson; a teacher might begin each lesson by asking students to think about the dimensions of a tangible object related to the topic, e.g. imagining a 3-dimensional image of blood vessels in a lesson on human anatomy. This is corroborated by McMain (2019), who stated that the ability to carry out any higher-order skill (in this instance mental rotation) evidences aspects of 'malleability and control' in the brain. One intervention that educators often use to support learning strategies such as mental rotation is the use of digital technologies. During an age of digitalisation, teachers have rapidly adapted to changing environments. Today's students benefit from technology through the use of whiteboards, tablets and, more recently, synchronous e-learning tools. Recent research into e-learning has seen numerous positive outcomes on specific cognitive and metacognitive abilities, such as the increased long-term retention of learning materials (Petretto *et al,* 2021). This further supports progress in classroom practice when discussing how the brain can adapt to new learning experiences. The successes of blended learning are testimonials to showing the brain's ability to understand new methods of embedding and accessing information to create more learning pathways.

Bringing attention back to the definition of plasticity being the brain's ability to undergo temporary or permanent changes (Tovar-Moll & Lent, 2016), we can identify multiple similarities between malleability and neuroplasticity. So, when examining malleability at a synaptic level, this would include the reorganisation of neural networks, which, as discussed previously, is a contributor to neural development (Bonfanti & Charvet, 2021). Therefore, one could then draw the conclusion that for mental rotation to take place the brain is required to plasticise. As such, the relationship between various tenets of spatial learning and malleability reveals itself as an intriguing area that may benefit from further study.

Bridging the gap between metacognition and plasticity

Truly, there lies a strong relationship between metacognition and neuroplasticity, making them an interesting pair to study. Each phenomenon has its dividing characteristics; however, there are several psychometric factors prevalent that, when analysed, link their anatomical foundations to suggest alternating influence. The journey within metacognition is often recognised once an individual begins to show high forms of psychological development, e.g. attitudes of self-actualisation described by Maslow and Lewis (1987). Be that as it may, when placing a lens on the anatomy, building blocks of psychological development can be traced back to the neural connectivity of the thalamus, hippocampus and prefrontal cortex (Drigas & Mitsea, 2021). An aspect of this is supported by Palombo *et al* (2015), who label the hippocampus as vital in the facilitation of learning. The importance here is not solely the brain region, but the emphasis on neural connectivity and the processes of learning where the number of synapses per neuron gradually increases (Anderson, 2011). This suggests that the quantity of neural circuits in the brain can change according to learning demand. As metacognition requires high cognitive skill, one can assume that the brain would recruit more synapses per neuron to meet increased demand. Surely such dynamic changes can be described using the definition of neuroplasticity, underlined in the introduction, being 'the brain's ability to undergo temporary or permanent change'.

If choosing to focus on a specific region, the hippocampus is exemplary when tying metacognition to plasticity. Within the systematic study of the temporal lobe, psychologists illustrate the major role that the hippocampus plays in how humans learn. Here, key observations have been made, including its role in simultaneously consolidating learning as well as converting information from working to long-term memory via electrical impulses (Sousa, 2016). These processes would be vital for students when carrying out information retrieval during both formative and summative assessments. Therefore, it may be beneficial for educators to achieve growth in the hippocampus by teaching using methods that encourage the build-up of more neural networks. Current examples of this may include dual-coding (audio alongside reading) where there is an emphasis on multisensory input, which has been shown to directly promote improved brain function (Lane & Schaaf, 2010). Furthermore, educators can incorporate new, in-depth, recall tasks (alternating assessment for learning strategies) within the lesson, where students will be required to change their typical thought patterns to access memory through active recall.

Developing these neural networks by linking and creating new pathways would not be made possible in the absence of plasticity, as this is what allows neurogenesis to occur. Thus, the theories of metacognition and plasticity must work in conjunction to promote cognitive development during an individual's learning journey.

Conclusion and recommendations for further research

Although ample research has taken place into each phenomenon in their singularity, when analysing the prevalence of metacognition and plasticity-based evidence in tandem, the literature is scarce. This study has identified the importance of this area in the development of teaching and learning. There have been clear references made to current strategies used in STEM learning to facilitate ideas of plasticity, but which do not yet evaluate how strong these links are to pedagogy. To truly understand the implementation of metacognitive strategies in classroom pedagogy, and link this with anatomical plasticity, researchers must be mindful of taking a multi-faceted approach that addresses all areas of study and builds upon current best practices. Efforts toward a combination of exchange of expertise and experimental applications could help to speed up the development of new studies and lead to eventual improvement of educational policies to better support learners throughout their cognitive development. I hope that this paper has opened the discussion for continued research into this area, and I summarise by posing the following questions: Should more efforts be made to focus on improving the neuroanatomy of learners? What do educators know about neuroplasticity, and do they consider this when teaching in classrooms? What pedagogical practices can be used to further promote neurogenesis?

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