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Informing practice in mathematics through the use of Herrmann's Whole Brain® theory

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In this research I explored how mathematics teachers can inform their teaching practice through a meta-reflective inquiry into methods of facilitating Whole Brain® learning in mathematics. Herrmann's Whole Brain® theory was used as a lens through which to explore leading theories in the fields of constructivism, mathematics education and cognitive psychology by means of a participatory action research innovation, stretching over approximately 3 years. An analysis of these theories validated Herrmann's Whole Brain® theory as the foundation for a synthesised integrated theory of practice, which also formed the epicentre of the conceptual framework for the research. The conceptual framework was also at the core of the participatory action research. The Herrmann Brain Dominance Instrument® (HBDI®) was administered to 8 teacher participants in a school mathematics department. Learners of each of the teacher participants also completed a questionnaire on how they perceived their teachers to facilitate learning and assessment of mathematics. These results were compared to the teacher participants' Herrmann's Brain Dominance Instrument®. Findings indicate that the Herrmann Brain Dominance Instrument® initiated scholarly reflection with teacher participants involved in facilitating and assessing the learning of mathematics. The collective reflexive practice was both part of the action research process and an outcome of the research itself. Findings also indicate that the thinking preferences of teacher participants, as tested by the Herrmann Brain Dominance Instrument®, are not necessarily indicative of their teaching style and teachers involved in post-graduate studies indicated an ability to access their non-dominant thinking mode situationally.

Keywords: collective reflexive practice; facilitating learning; Herrmann Brain Dominance Instrument®; Herrmann's Whole Brain® Theory; informing theory through practice; learning theories; participatory action research; scholarly reflection; Senior Phase mathematics; thinking preferences

Introduction

In this article I report on the research that developed as a result of personal reflection on my thinking and learning preferences after being introduced to the Herrmann Brain Dominance Instrument® (HBDI®). As a Senior Phase[i] mathematics teacher with a specific interest in supporting learners who find mathematics challenging, I was interested in the possible application of Herrmann's Whole Brain® theory to facilitate and assess learning in mathematics. Although Herrmann (1995) originally developed the HBDI® to inform communication, teamwork, training, planning and creativity within corporations, the instrument has more recently also been used in education to meet the same objectives. Steyn and Maree (2002) considered Herrmann's Whole Brain® theory in terms of the learning preferences and study orientation to mathematics of first-year engineering students, but the theory has to date not yet been explored in the context of mathematics education at school level. De Boer, Bothma and Du Toit (2011) also used Herrmann's Whole Brain® theory as foundation for their multi-disciplinary study with a group of first-year information literacy students. Although they constructed a comprehensive Whole Brain® model from their findings in this and previous longitudinal studies, the comprehensive Whole Brain® model is not specific to mathematics. With this study I aimed to contribute to the body of the knowledge regarding the application of Herrmann's Whole Brain® theory, specifically in the context of facilitating and assessing mathematics at school level of learners between 12 and 15 years old.

Herrmann's Whole Brain® Model amalgamates Sperry's hemispheric left and right brain theory and McLean's triune brain into a metaphorical four-quadrant representation of the brain, each associated with a particular set of thinking modes (Herrmann, 1995). This metaphorical four-quadrant Whole Brain® Model, shown in Figure 1, indicates the A or cerebral left quadrant, B or limbic left quadrant, C or limbic right quadrant and D or cerebral right quadrant. An individual will have certain preferences for these different thinking and learning modes which can be measured and quantified by the HBDI®.

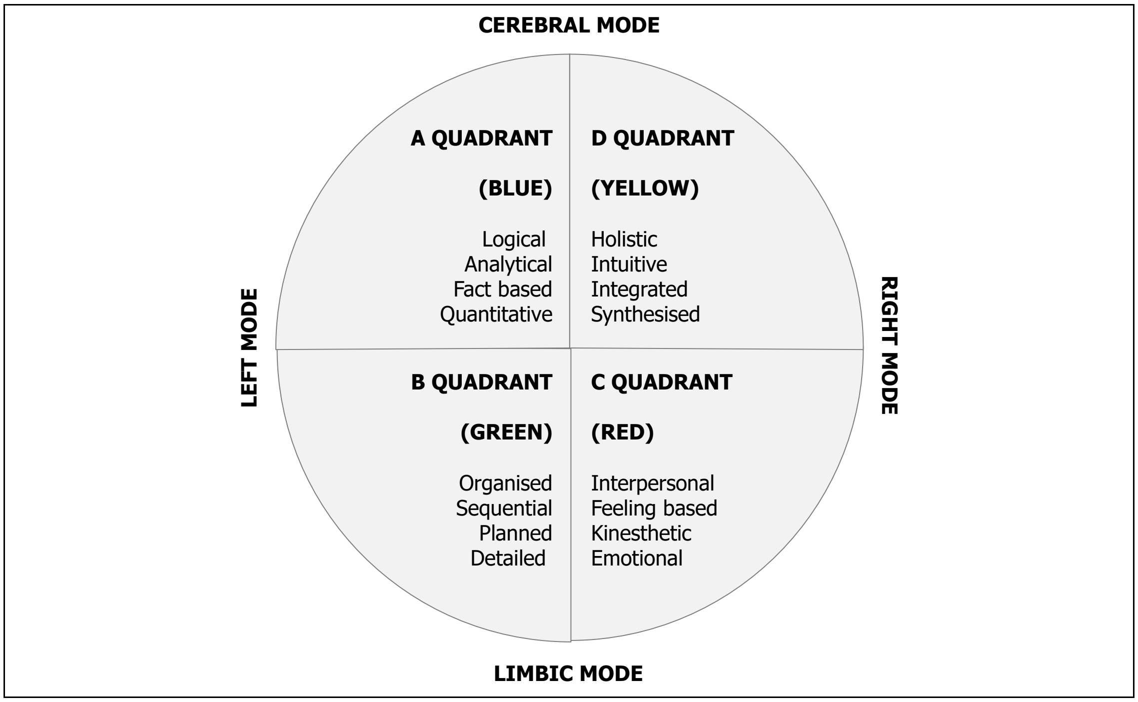


Figure 1 Herrmann's Whole Brain® Model (Randewijk, 2019:3)

An understanding of Herrmann's Whole Brain® Theory could aid teachers in their planning of learning opportunities that would engage learners with different thinking and learning preferences. Complementary to this is each teacher's understanding of his or her own thinking and learning preferences along with the thinking and learning preference of the individuals in their community of practice. For this reason, the HBDI® was used to determine each teacher participant's thinking preferences. Hattie and Yates (2013:24) state that "those teachers who are students of their own effects are the teachers who are the most influential in raising students' achievement." The HBDI® was, therefore, also used to initiate scholarly reflection among teacher participants to inform their practice. The term "research innovation" is used to describe the action of initiating and reflecting on a new idea towards facilitating and assessing mathematics in the Senior Phase. I considered two questions in this research. Firstly, how could Herrmann's Whole Brain® Theory be used as the foundation to an integrated theory of practice that could be represented in a mathematics-specific Whole Brain® model to inform practice for diverse learner needs in mathematics? Secondly, how could the Herrmann Brain Dominance Instrument® be used to initiate reflexive practice among the teacher participants?

The setting of this research was an independent school in South Africa where I taught and am currently teaching. At the time of the research the eight teacher participants were all members of the Secondary Faculty Mathematics Department and were all involved in teaching learners in the Senior Phase. All participants held at least a bachelor's degree with mathematics as subject and a postgraduate certificate in education. The teacher participants comprised two young female teachers with less than 5 years' teaching experience; one male teacher with around 10 years' teaching experience; a more experienced male teacher working towards a master's in education at the time; a more experienced female teacher working towards a PhD in education at the time; a more experienced female teacher in a managerial position; two veteran male teachers of which one had obtained a masters in mathematics. In this particular school learners in Grade 7 form part of the Secondary Faculty.

Literature Review

In the review of the literature I came across the seminal work of Herrmann's (1995) Whole Brain® theory. This theory became the perspective from which the teacher participants facilitated and assessed mathematics in their Senior Phase classes. I used the principles of the theory to analyse leading constructivist and psycho-mathematics theories. It was, therefore, important to firstly consider Herrmann's Whole Brain® theory and its application to teaching, since this theory has become the principal theory at the core of this research.

Herrmann (1996) explains how learners' thinking could be activated by tasks focussing on their thinking and learning preferences. These preferences for the different quadrants can be summarised as follows.

Learners that have a preference for the A quadrant are generally activated by activities and tasks that require quantifying, analysing, theorising and logical processing. Learners with a preference for the B quadrant are activated by activities and tasks that require them to organise, practise skills and do sequencing. Learners who prefer thinking preferences from the C quadrant are activated by activities focussed on moving, feeling, sharing, being involved, as well as internalising knowledge. Learners with a preference for the D quadrant are activated by tasks that focus on exploring, discovering, conceptualising and synthesising.

Herrmann (1996:152) states that an awareness of and sensitivity for differences are important to keep all learners in class engaged, since a "turned-off learner is a waste of educational time." This active engagement is in line with Slabbert, De Kock and Hattingh (2009) who advocate that learners should be actively engaged in problem-solving in order to conceptualise the mathematics involved in real-life problems. Furthermore, leading theories in education advocate a "collaborative-constructivist approach to learning" (Garrison, 2003:57). It was, therefore, important to review the theories underpinning collaboration, constructivism and problem-solving for the purpose of this research, which I considered to be innovative. This was done to determine whether these theories supported Herrmann's Whole Brain® approach to learning.

A short overview of these theories is presented in order to validate the need for a Whole Brain® approach to mathematics and to provide background on the development of the conceptual framework of the research.

According to Mulcahy (2007), Dewey was one of the earliest advocates of constructivism, which he considers to be a process where learners are actively involved in problem-solving. Problem-solving is the vehicle through which understanding is constructed. Dewey explains the process of problem-solving as a process of inquiry, interpretation, contextualisation and analysis of the given problem, the consideration of possible solutions, execution of the chosen solution and finally reflection and validation of the findings.

In terms of Herrmann's Whole Brain® theory, Dewey's approach to problem-solving can be interpreted as follows: inquiry, contextualisation, interpretation and validation can be associated with the D quadrant; analysis and proposing possible solutions can be associated with the A quadrant; execution of the proposed solution can be associated with the B quadrant; and reflection can be associated with the C quadrant.

Vygotsky supports Dewey's approach to (constructivist) problem-solving and adds that the process could be augmented by cooperative learning or scaffolding (Mulcahy, 2007). Bukatko and Daehler (2012) define Vygotsky's notion of scaffolding as a process through which collaboration takes place prior to problem-solving that is supported through structured instruction, which includes defining, demonstrating and supporting. Vygotsky advocates support structures to problem-solving from the B quadrant by means of structured facilitation of learning, as well as from the C quadrant by means of collaboration or cooperative learning.

Along with Dewey, Bruner and Olsen (1973) also state the importance of learning by means of experience, but it was Bruner's student, Dienes (1971), who focussed his attention on experiential learning specifically in terms of mathematics education. We thus considered both Bruner's and Dienes' constructivist learning theories in terms of Herrmann's Whole Brain® theory.

Similar to Dewey's and Vygotsky's process of problem-solving, Bruner (2009) distinguishes four principles underlying the facilitation and assessment of learning, namely intuition, structure, scaffolding and motivation. These can be situated in the following quadrants: intuition (like Dewey's inquiry) in the D quadrant, structure and scaffolding in the B quadrant and motivation in the C quadrant.

Bruner, like Piaget, further distinguishes between three different levels of knowledge acquisition and understanding, which he calls enactive, iconic and symbolic: "enactive", referring to actively manipulating physical objects (which can be associated with Herrmann's C quadrant); "iconic", referring to using visual representations (which can be associated with Herrmann's D quadrant); and "symbolic"', referring to formal abstract calculations in order to come to a new understanding (which can be associated with Herrmann's A quadrant). These are not linear levels of development. At any stage an individual can revert to the enactive or iconic level when faced with a challenging new problem (Saran, 2007). The acclaimed Singapore mathematics curriculum is based on Bruner's enactive, iconic and symbolic stages, but reworded as concrete, pictorial and abstract, or in short, CPA (Wong, 2015).

Dienes (1971) was the father of psycho-mathematics, a field of research referring to the psychology of mathematics. His work extended Bruner's three levels of knowledge to six levels of engagement.

The first level is that of free play, or trial and error, like Bruner's enactive level, and can be associated with the C quadrant. The second level is that of play by the rules, which gives some structure to the exploration of level one. This structure can be achieved by scaffolding and is associated with Herrmann's B quadrant. The third level is that of comparison. It is an effective organisational strategy that could be associated with the B quadrant. When the comparison is used to aid analysis, it can also be associated with the A quadrant in order to contextualise the problem, which is associated with the D quadrant. Structuring and representation of information is the fourth level and can be associated with the A, B and D quadrants, because of its analytical, structured, and contextualised approach. The fifth level is that of symbolisation, which is associated with the A quadrant. Similar to symbolisation, formalisation as the sixth level can be associated with the A quadrant.

Dienes' (1971) approach to problem-solving bears similarities to that of Pólya's extensive research into problem-solving on which Boaler (2009) bases her inquiry-based learning. She is also an advocate of "talking about mathematics", a process which she uses to activate learners' thinking, which is in line with Herrmann's C quadrant. Furthermore, Boaler (2009:185–186) emphasises organising one's thoughts by "drawing the problem, making a chart with the numbers (and) trying a smaller case." Drawing the problem can be associated with Bruner's iconic phase and Herrmann's D quadrant, whereas making a chart and trying a smaller case is similar to Dienes' structure and representation, associated with the A, B and D quadrants.

The importance of a Whole Brain® approach to problem-solving in mathematics is evident in the research by Dewey, Vygotsky, Brunes, Dienes and Boaler as well as in the Singaporean CPA approach. These researchers all advocate a multi-quadrant approach to acquiring knowledge in order to develop an understanding of mathematics, but it was also important to consider the different types of knowledge itself. I also include Krathwohl's "four knowledge dimensions", namely, factual, procedural, conceptual and metacognitive knowledge. Krathwohl added the fourth dimension of metacognition as an extension to Bloom's taxonomy (Krathwohl, 2002).

It is important to note that these knowledge dimensions form part of "a complete taxonomy" designed by Bloom (1956:7) which consists of "three major parts – the cognitive, the affective, and the psychomotor domains." As Herrmann does, Bloom recognises the importance of the limbic right quadrant, which he describes as the affective domain in learning. The affective domain is important for "changes in interest, attitudes, and values, and the development of appreciations and adequate adjustment" (Bloom, 1956:7).

Along with Bloom's affective domain, which I position in the C quadrant, I also categorise each of the knowledge domains according to quadrants. I position factual knowledge in the A quadrant, procedural knowledge in the B quadrant and conceptual knowledge in the D quadrant. Metacognition, according to Flavell (1979:908) "can lead you to select, evaluate, revise, and abandon cognitive tasks, goals, and strategies in light of their relationships with one another and with your own abilities and interests with respect to that enterprise." Metacognition as a self-regulated reflexive process can thus be considered to be a Whole Brain® process. For this reason, I place it in the centre of the proposed comprehensive mathematics-specific Whole Brain® Model (cf. Figure 3), which is further discussed under the conceptual framework.

Bloom's knowledge dimensions are also in line with the Singaporean approach of concepts, skills, attitudes, processes. The Singapore Mathematics Pentagonal Model (Lim-Teo, 2002) (cf. Figure 2) considers concepts, skills, attitudes, processes as well as the significance of metacognition in problem-solving. I consider concepts or topics in mathematics to be associated with the A quadrant, skills with the B quadrant, attitudes with the C quadrant and processes with the D quadrant.

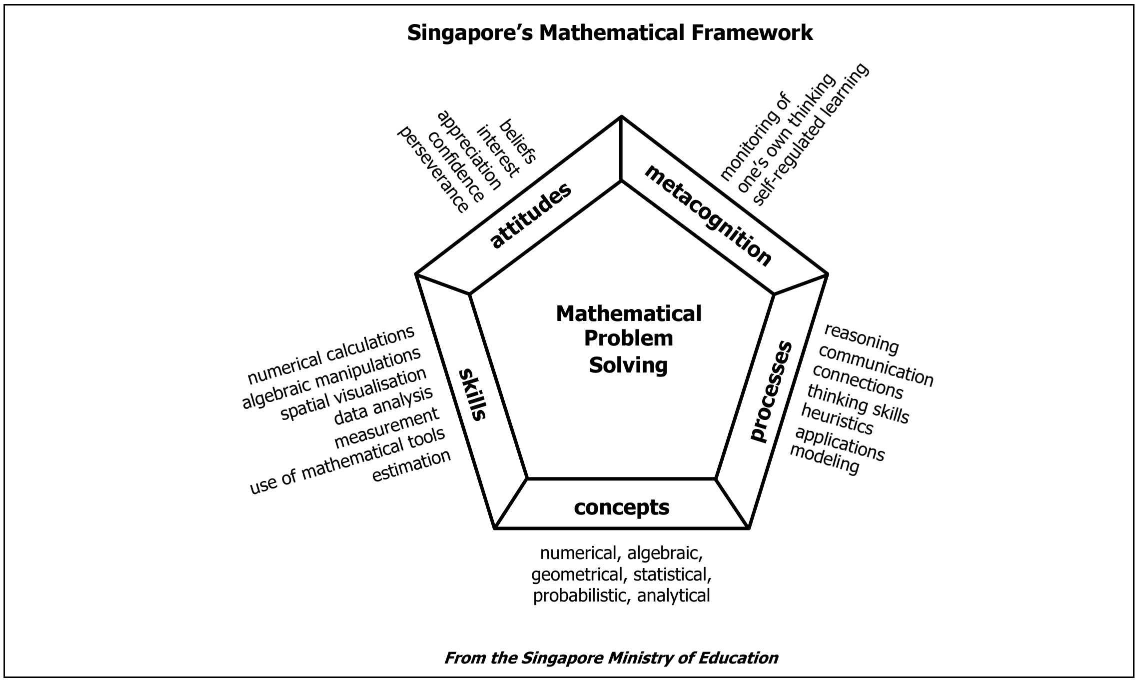


Figure 2 The Singapore Mathematics Pentagon Model (Randewijk, 2019:67)

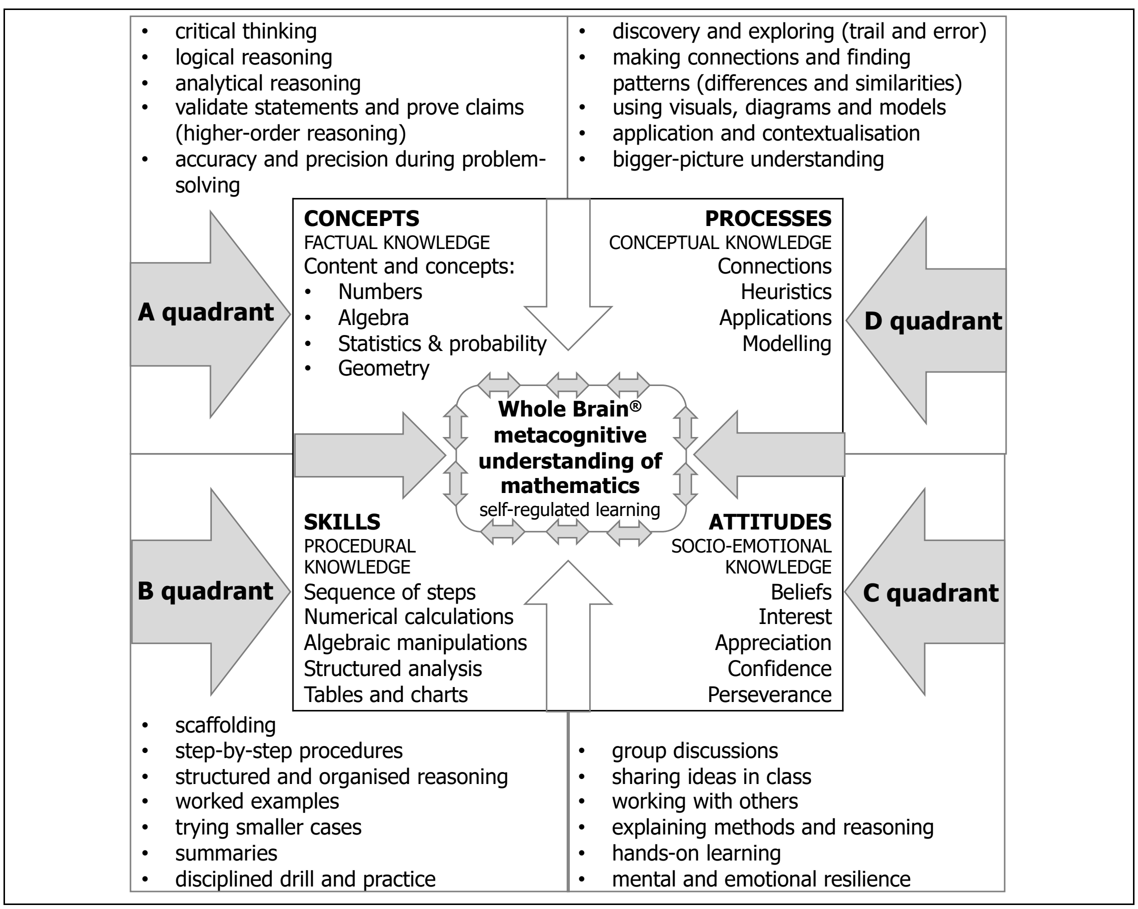


Figure 3 Comprehensive mathematics-specific Whole Brain® Model for facilitating learning in mathematics (Randewijk, 2019:237)

Conceptual Framework as an Integrated Theory of Practice

Derived from the literature review I considered constructivist and psycho-mathematics theories as well as theories specific to facilitating and assessing learning in mathematics in order to validate the use of Herrmann's Whole Brain® theory. Furthermore, I synthesised existing educational theories in terms of Herrmann's Whole Brain® Model into a new proposed comprehensive mathematics-specific Whole Brain® Model (cf. Figure 3).

My understanding of these theories as well as the linking of aspects of these theories to each of Herrmann's quadrants, were refined throughout my reflexive process. It was a living theory, constantly being revisited and developed as a result of my own metacognitive reflection. The term living theory is often used by international scholars of note such as McNiff and Whitehead (2000). A Whole Brain® metacognitive understanding of mathematics is placed at the centre of the proposed comprehensive mathematics-specific Whole Brain® Model. As the arrows (cf. Figure 3) indicate, metacognition is a Whole Brain® process and also an objective of teaching – to guide learners towards a self-reflexive awareness of their thinking processes. A Whole Brain® metacognitive understanding of mathematics can, therefore, only be obtained through an understanding of factual, procedural, socio-emotional and conceptual knowledge, as indicated in the inner square in Figure 3. These knowledge types draw on both Krathwohl's (2002) knowledge dimensions, as well as the Singapore Mathematics Pentagon Model (Lim-Teo, 2002). The acquisition of these different knowledge types can be facilitated through methods set out in the outer squares of each quadrant. These methods draw on the constructivist problem-solving approaches advocated by Dewey, Vygotsky, Brunes, Dienes and Boaler.

The proposed comprehensive mathematics-specific Whole Brain® Model is not only the conceptual framework, but is also proposed as a model, similar to that of the Singapore Mathematics Pentagon Model (Lim-Teo, 2002:5), for an integrated theory of practice in planning learning opportunities in mathematics. The proposed comprehensive mathematics-specific Whole Brain® Model is in itself a product of reflexive action research. The conceptual framework addressed the first research question of how Herrmann's Whole Brain Theory® could be used to develop an integrated theory of practice for the facilitation and assessment of mathematics in the Senior Phase. It also aids the second research question of how the Herrmann Brain Dominance Instrument® can be used to initiate both personal and collective reflexive practice within a mathematics department.

Research Methodology

Since I advocate that practice is informed by means of metacognitive reflection, it was important that the research design was also reflexive in nature. For this reason, action research, and more specifically, participatory action research, was used as the research approach. McNiff and Whitehead (2000:15) define action research as "an enquiry by the self into the self" in a collaborative setting where participants are also actively engaged in the learning. The research is also a reflexive learning experience through active engagement.

Ehrhart (2002:1) states that participatory action research is an "empowering" process by which collaboration leads to a new enriched understanding of oneself, one's relationship with those around one as well as with the world. For this reason, collective and individual reflexive practices were used to examine and report on the findings – especially since the reflexive practice was in itself an objective of the research. As stated earlier, Hattie and Yates (2013:24) justify the importance of reflexive practice by stating that teachers who engage in such practices positively influence their learners' performance in mathematics.

The mathematics department at the school where I was (and am currently) employed, comprised nine members of staff at the time of the study. All eight mathematics colleagues agreed to take part in the research. The school is an independent school on the West Coast of South Africa, where professional development of teachers is highly valued. I consider continuing professional development of teachers to be imperative, as does Kennedy (2005).

Both qualitative and quantitative data were collected on the thinking preferences of each teacher participant by means of a pre-innovation questionnaire, the HBDI®, interviews and informal reflective conversations. The pre-innovation questionnaire was used to determine participants' insights into what they perceived their thinking preferences to be and what they deemed to be important factors in facilitating mathematics. The pre-innovation questionnaire, together with the HBDI® itself, which tested participants' actual thinking preferences, were used to start the reflexive action research process and initiated several conversations in the months that followed. Data were also collected from the learners of each of the teacher participants. This was done by means of a questionnaire designed to determine learners' perceptions regarding their teachers' approach to teaching mathematics. For seven of the participants the data consisted of over 40 learner feedback questionnaires, but as the eighth participant held a management position and taught fewer learners, this number was only 15. In total, 395 learners completed the questionnaire. Both the pre-innovation questionnaire and the learner questionnaire were designed on the tenets of Herrmann's Whole Brain® theory, but with a focus on determining mathematical teaching, learning and assessment approaches. However, participants were not informed which descriptions matched which quadrant. The results of both questionnaires could, therefore, be classified and quantified according to each of Herrmann's four quadrants. This was done to compare the perceived quadrant preferences with those of each teacher participant's actual preferences, as determined by the HBDI®. Feedback on learners' perceptions of their teacher's teaching was given to each of the teacher participants in order to continue the reflexive conversations initiated by the pre-innovation questionnaire and HBDI®.

Since the HBDI® is in itself a mixed-methods instrument, using a mixed-methods approach in this research was fitting. De Boer, Du Toit, Scheepers and Bothma (2013:10) justify this claim by stating that the HBDI® is "visual representation … rich with quantitative data. The working, interpretation and visual representation on the other hand, offers qualitative data that perfectly fit a mixed-method approach towards studying the application of Whole Brain® principles in the context of learning and facilitating learning." Data gathered from each teacher participant's pre-innovation questionnaire, his or her HBDI® scores, as well as the learner feedback questionnaires, were quantified according to quadrants. Although the quantitative data gave insight into each teacher's approach to facilitating and assessing learning, the qualitative reflection on these findings gave meaning to the trends that emerged.

To illustrate each teacher participant's reflexive practice cycles, I designed the Action Research Rope Model (cf. Figure 4). Since Herrmann's Whole Brain® Theory was used to initiate this research, it is indicated as the core fibre of the rope. My personal reflection on Herrmann's Whole Brain® Theory forms the first strand of the rope around the core fibre of theory. The teacher participants' reflexive practice weaves the next strand around the core. This strand is made up of their cyclic reflexive process of action informed by knowledge, and reinforced by new knowledge in turn informing their actions. The collective reflexive practice of the teacher participants draws the teacher participant group together into a close-knit community of practice, represented by the rope itself, all reflecting on Herrmann's theory. Although the research was actively conducted over a period of approximately 2 years, my own reflexive practice continued well beyond. This scholarly reflection was not only as a result of analysing the data findings, but also due to sporadic, informal conversations with the teacher participants in this study. These discussions also indicated their continuous reflection as initiated by this research.

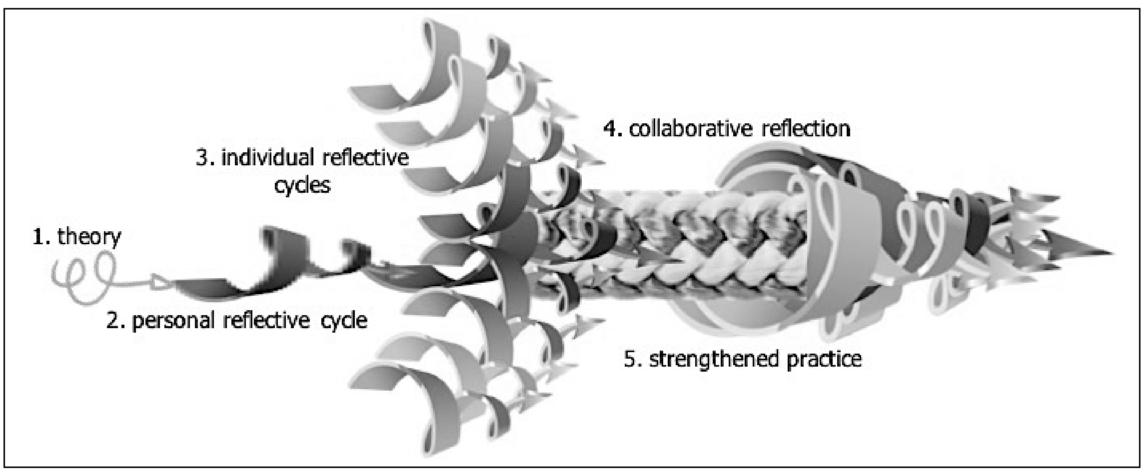


Figure 4 Randewijk's Rope Model depicting the reflexive nature of participatory action research (Randewijk, 2019:19)

According to Bunderson (1990:1) the HBDI® "provides a valid, reliable measure of human mental preferences" and, therefore, the use of a valid instrument contributes towards the validity of this study. The questionnaires to both teachers and learners were also designed on the principles of the HBDI® with the aim to create equally valid instruments. Furthermore, the literature review validated the use of Herrmann's Whole Brain Theory®, which provides construct validity to the study. Triangulation was used in two ways. Firstly, by determining each teacher's HBDI® profile and comparing it to each teacher's pre-innovation questionnaire and learner feedback form, it was possible to gain insight into each teacher's true practice. Secondly, the theory informing the practice, the practice itself and the reflection on both the theory and practice, aided the continuous process of informing both theory and practice. Since the participatory action research involved continuous discussions with participants, member checking was built into the process as an additional form of validation.

Since this research was conducted in an independent school in South Africa, permission was obtained from the Managing Director of the school. Participant consent forms were obtained from the eight teacher participants as well as parents of learners willing to participate in the study. These consent forms were in accordance with the guidelines set by the Ethics Committee of the University of Pretoria that granted ethical clearance for the study.

Data Analysis

The HBDI® was administered to each teacher participant by a qualified HBDI® practitioner. The HBDI® questionnaire consists of 120, mostly multiple-choice questions. Although an individual completing the questionnaire would not be aware of this, the multiple-choice options have been pre-categorised according to Herrmann's four quadrants. It was thus possible to determine an individual's preferences for each of the four quadrants upon analysing their responses. The computer-generated HBDI® profiles are comprehensive individualised profiles issued by Herrmann International and for this reason the questionnaire itself is not available to the public and can only be administered by an HBDI® practitioner. Although the profiles are computer generated and include detailed information on an individual's profile, the interpretation and debriefing for an individual to understand this unique profile is done by a qualified HBDI® practitioner.

The HBDI® questionnaire responses are categorised according to Herrmann's four quadrants and the resultant profile shows a quantified measure of the degree to which an individual prefers each of Herrmann's four quadrants. This is indicated on Herrmann's four-quadrant Whole Brain® Model in the form of two quadrilaterals: a solid-lined quadrilateral indicating the individual's profile and a dotted-line quadrilateral indicating the individual's adjective pair score or stress profile (Bunderson, 1990). The HBDI® indicates an individual's thinking preferences under normal conditions (indicated by the solid line) as well as under stressful conditions (indicated by the dotted line). The stress profile is tested by forcing participants to choose between two opposing thinking modes in order to determine an individual's preference when forced to make a choice. Herrmann (1995), validated by Bunderson (1990), believed that this forced choice would give insight into an individual's thinking preference within a forced or stressful situation, where it would be challenging to think and act according to their preferred thinking modes.

My personal HBDI® profile is indicated in Figure 5. It illustrates both the different quadrilateral lines, and also acts as the foundation of my personal reflexive practice. The solid line quadrilateral indicates my preferences for the A and D quadrants, whereas the adjective pair score indicates a shift away from the A quadrant towards the B quadrant. This entails my becoming less logical analytical and more focussed on completing an organised list of tasks. All participants' profiles are indicated in Figure 6. Table 1 below provides a quantified measure of the preferences that each participant indicated for each of Herrmann's four quadrants based on the results of their HBDI® questionnaires.

Table 1 Teacher participants' HBDI® profile scores (adapted from Randewijk, 2019)

	A quadrant	B quadrant	C quadrant	D quadrant
Participant 1	59	75	113	59
Participant 2	69	119	66	39
Participant 3	104	77	77	48
Participant 4	101	83	47	56
Participant 5	114	78	48	26
Participant 6	110	110	41	32
Participant 7	99	81	42	56
Participant 8	68	54	78	98

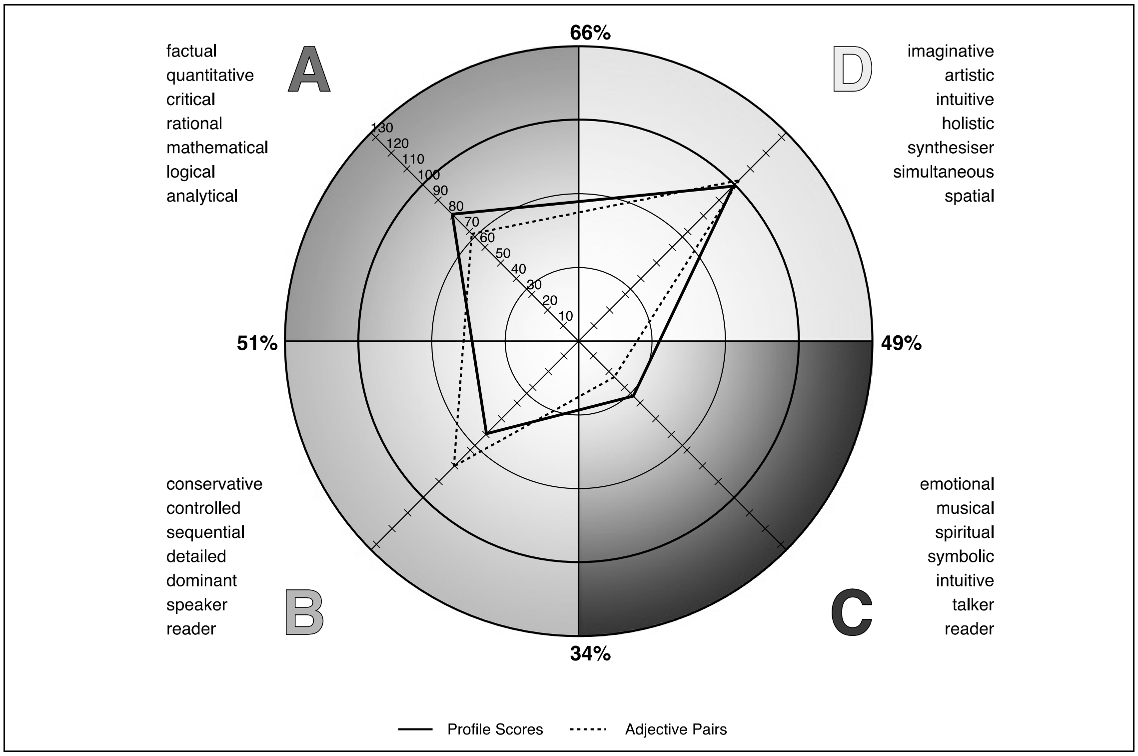


Figure 5 HBDI® profile indicated as a solid line and the HBDI® adjective pair score indicated as a dotted line

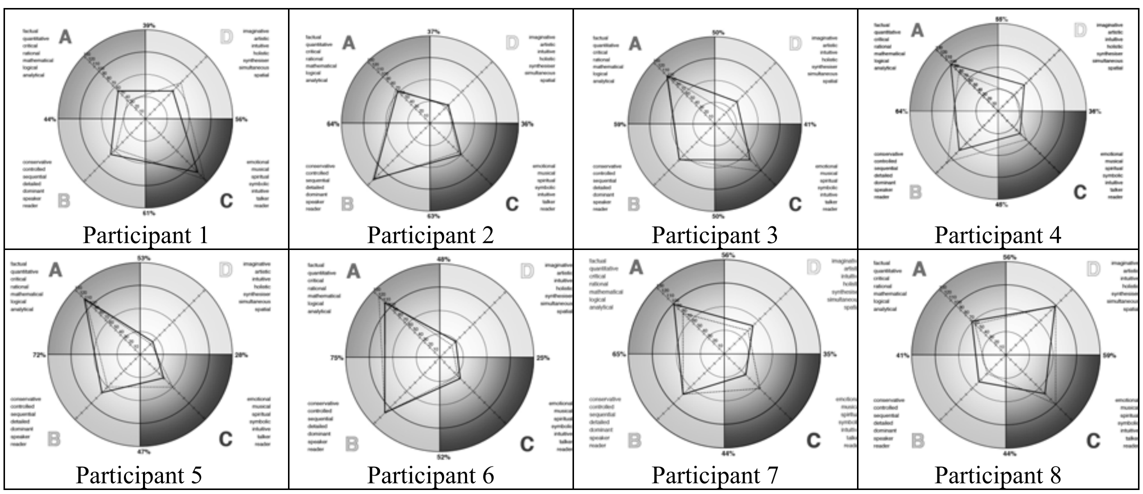


Figure 6 Individual HBDI® profiles of the eight teacher participants (adapted from Randewijk, 2019)

The teacher participants' pre-innovation questionnaires, as well as the learner feedback questionnaires were designed to include an equal number of descriptors relating to each of Herrmann's four quadrants. This made it possible to quantify the results according to the four quadrants. In order to represent my findings in accordance to Herrmann's four-quadrant Whole Brain® Model, I chose a simple four-sector pie chart indicating the preference for each of the quadrants. A selection of tables and figures are included below.

In Table 2 the teacher participants' perceptions on the nature of mathematics are summarised and the corresponding representation is presented in Figure 7.

Table 2 Perception on the nature of mathematics teachers' pre-innovation questionnaire; Question 1 – I consider mathematics to be a subject that … (choose three) (adapted from Randewijk, 2019)

A quadrant	B quadrant	C quadrant	D quadrant
seeks to validate statements and prove claims (3)	is about practicing and evaluating ideas	requires active participation during the learning experience (4)	is a process of discovery and exploring new ideas (3)
relies on subject matter expertise (2)	is about being organised and consistent (1)	is an opportunity to challenge and motivate learners (3)	allows for intuition and educated guessing
emphasises accuracy and precision during problem-solving (2)	is about practical application (1)	is an opportunity to collaborate and share ideas (1)	requires a conceptual (bigger picture) understanding (4)
7 of 24 (29%)	2 of 24 (8%)	8 of 24 (34%)	7 of 24 (29%)

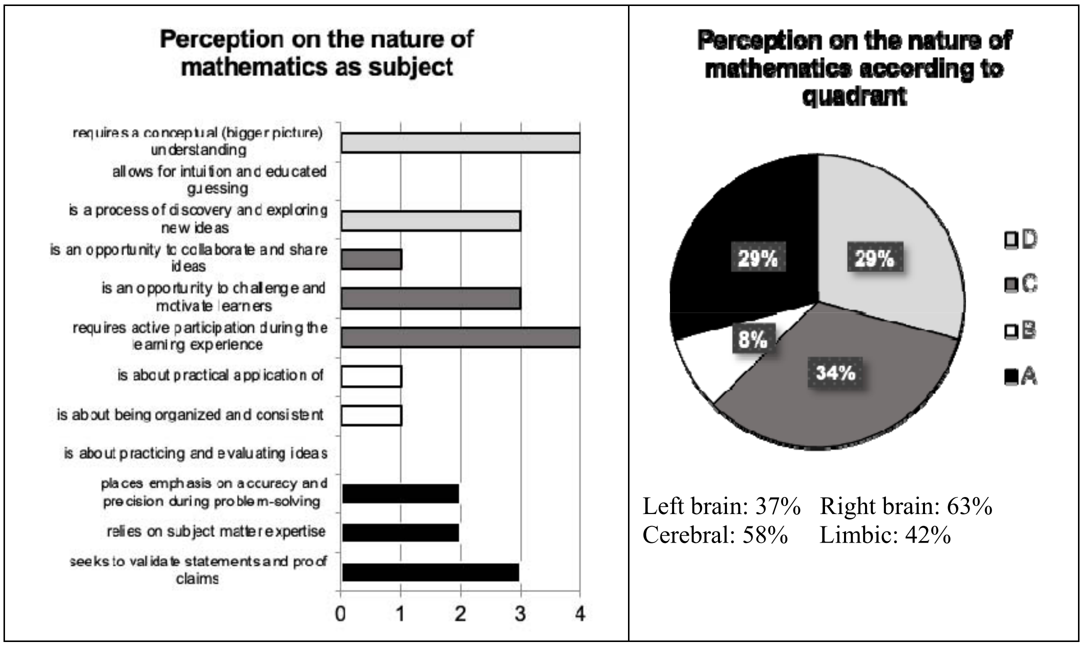


Figure 7 Teacher participants' perceptions of the nature of mathematics (Randewijk, 2019:185)

Data from the teacher participants' pre-innovation questionnaires were also compared to the learner feedback questionnaires, where questions were of a similar nature. For the learner questionnaire, descriptors were phrased somewhat differently in order to make the meaning more understandable to learners. Table 3 compares what teachers deemed to be the key feature of mathematics, to how learners perceived their teachers to view mathematics. Figure 8 summarises the findings into two comparable four-quadrant representations.

Table 3 Teacher participants' views of the key features of mathematics compared to what learners perceived their teachers' view to be based on Question 1 of the learner questionnaire (adapted from Randewijk, 2019)

Teacher frequencies Key features of mathematics			
A quadrant exact science	B quadrant procedural problem-solving	C quadrant human activity	D quadrant continuous process of discovery
1 of 8 (13%)	3 of 8 (37%)	0 (0%)	4 of 8 (50%)
Learners' frequencies Question 1: When my teacher talks about mathematics, (s)he explains it as …			
A quadrant a logical and analytical process	B quadrant step-by-step instructions to follow	C quadrant an opportunity to share ideas and methods	D quadrant a process of discovery and making connections
91 of 395 (23%)	162 of 395 (41%)	46 of 395 (12%)	96 of 395 (24%)

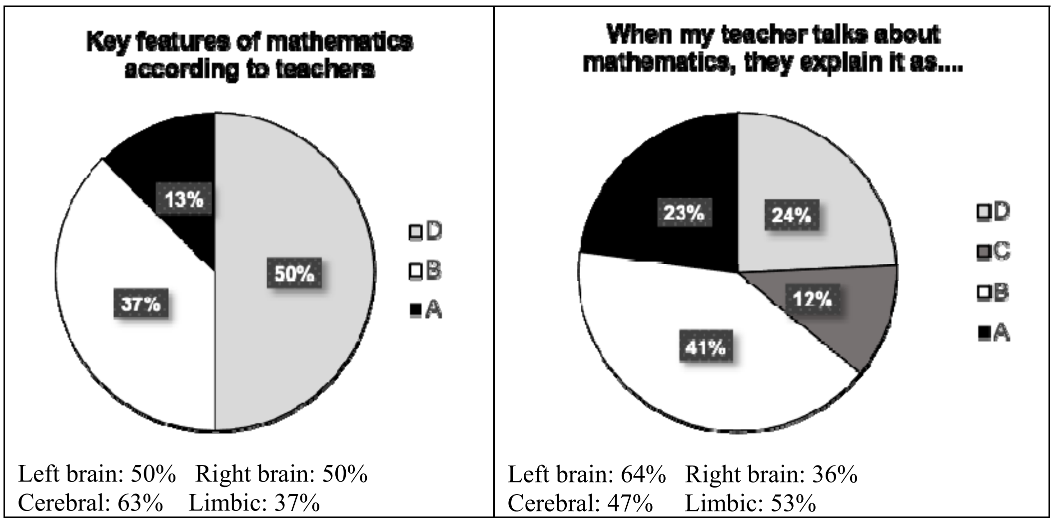
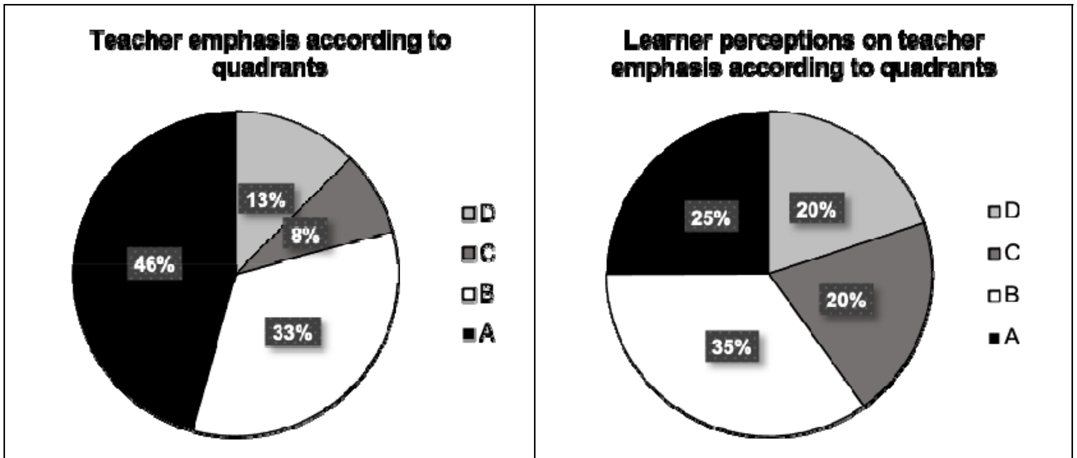


Figure 8 Teacher participants' views of the key features of mathematics compared to what learners perceived their teachers' views to be

Table 4 indicates the thinking patterns and processes that teachers encouraged in their classrooms compared to what learners perceived their teachers emphasised. The findings are summarised as two comparable four-quadrant representations in Figure 9.

Table 4 Teacher participants' perceptions of the thinking patterns and processes they encouraged compared to what learners perceived their emphasis to be based on Question 2 of the learner questionnaire (adapted from Randewijk, 2019)

Teacher frequencies Thinking patterns and processes encourages (choose three)			
A quadrant	B quadrant	C quadrant	D quadrant
critical thinking = 3 logical reasoning = 6 higher-order reasoning = 2	step by step = 4 examples = 1 organisation of thoughts = 3	group discussions = 0 sharing ideas = 0 active participation = 2	brainstorming = 2 pattern recognition = 1 creativity = 0
11 of 24 (46%)	8 of 24 (33%)	2 of 24 (8%)	3 of 24 (13%)
Learners' frequencies Question 2: My teacher places a lot of emphasis on … (choose three)			
A quadrant	B quadrant	C quadrant	D quadrant
critical thinking = 82 logical reasoning = 97 problem-solving = 97	step by step = 179 examples = 139 structuring my work = 66	explaining = 104 working with other = 45 sharing ideas = 73	drawings/diagrams = 60 finding patterns = 87 trial and error = 73
276 of 1,102 (25%)	384 of 1,102 (35%)	222 of 1,102 (20%)	220 of 1,102 (20%)



Left brain: 79% Right brain: 21%
Cerebral: 59% Limbic: 41%

Left brain: 60% Right brain: 40%
Cerebral: 45% Limbic: 55%

Figure 9 Teacher participants' perceptions of the thinking patterns and processes they encouraged compared to what learners perceived their emphasis to be according to quadrants (Randewijk, 2019:187)

In order to gain insight into how learners prepared for their assessments in mathematics, they were asked to indicate which of the following methods they employed. The results are summarised in Table 5.

Table 5 When I prepare for a test, I like to … (tick all that apply) (adapted from Randewijk, 2019)

A quadrant	B quadrant	C quadrant	D quadrant
go through the homework questions I got wrong to understand where I went wrong and what to watch out for (I like to focus on the details) (122)	study examples and step-by-step procedures to solve problems (practise!) (240)	study with a friend (or friends) so that we can explain to each other (73)	find connections (differences and similarities) between the different topics so that I can distinguish between them (I like to see the bigger picture) (53)
25%	49%	15%	11%
122 of 488	240 of 488	73 of 488	53 of 488

Quantitative Data Findings

When all of the teacher participants' unique profiles were combined, as indicated in Figure 9, it produced a composite Whole Brain® profile. This supports Herrmann's (1995:10) notion that every sizeable group would consist of a "composite whole brain." It also shows that there is no specific set of thinking preferences unique to mathematics teachers. The composite profile scores compared to the teacher participants' adjective pair scores are indicated in Figure 9. Collectively, the teacher participant group's profile scores for the respective quadrants can be quantified as predominantly A, at 31%, B at 28%, C at 21% and D at 20%.

The pre-questionnaire results from the eight teacher participants indicate that they perceived the nature of teaching mathematics to be predominantly focussed on quadrants A, C, and D. Each teacher could indicate three descriptors that they perceived to be the nature of mathematics. Only two of the 24 responses could be categorised in the B quadrant. This is in contrast to eight of 24 responses categorised in the C quadrant with its interpersonal focus, which could be indicative of the value that teachers placed on the human activity of teaching, rather than on the delivery of mathematical content. The C quadrant descriptors chosen by teachers were those of active participation during the learning opportunity – an opportunity to challenge and motivate learners, and an opportunity to collaborate and share ideas. These results are presented in Table 2 and Figure 7.

In contrast to the teachers' perceptions on the nature of teaching mathematics, four of the eight participants considered the key feature of mathematics to be a "continuous process of discovery", a D-quadrant focus. Three of the participants considered the key focus to be "procedural problem-solving", a B-quadrant focus and only one participant considered it to be an "exact science", an A-quadrant focus. None of the participants considered mathematics to be a "human activity." These results correspond to the learners' perceptions on what they considered their teachers' focus in mathematics to be. Only 46 of 395 (12%) learners considered mathematics as an opportunity to share ideas and methods, which corresponds with mathematics as a "human activity." Unlike the teacher participants, 162 of 395 (41%) learners indicated that they perceived their teachers to consider mathematics as a set of step-by-step instructions to follow with only 96 of 395 who thought that their teachers considered mathematics to be a process of discovery. These findings are summarised in Table 3 and Figure 8.

The thinking patterns and processes that teacher participants perceived themselves to encourage in their respective mathematics classrooms were predominantly focussed in quadrants A and B. Quantified according to quadrant, focus on quadrant A was 46% (11 of 24), 33% (eight of 24) on quadrant B, 8% (two of 24) on quadrant C and 13% (three of 24) on quadrant D. Yet, based on the learners' responses, the focus was more evenly spread among the quadrants with a somewhat higher preference for quadrant B at 35% (384 of 1,102), quadrant A at 25% (276 of 1,102), quadrant C at 20% (222 of 1,102) and quadrant D at 20% (220 of 1,102). Although the teacher and learner groups perceived the thinking patterns and processes that teachers emphasised to be left-brain dominant (quadrants A and B), the learners did not perceive the emphasis to be as strong as the teachers did. These results are summarised in Table 4 and Figure 9.

Although the learners' preferences for the different quadrants were not formally tested, results from the learner questionnaires indicate a reasonably balanced Whole Brain® profile, supporting the need for a Whole Brain® approach to facilitating learning and assessment in mathematics. However, 240 of 488 (49%) responses indicate that learners preferred to study examples and step-by-step procedures to solve problems. Only 53 of 488 (11%) responses indicate that learners studied by means of employing D-quadrant skills, with a view to finding connections (differences and similarities) between the different topics so that they can distinguish between them. These results are summarised in Table 4.

As considered earlier, 162 of 395 (41%) learners considered their teachers to explain mathematics from a B-quadrant approach as presented in Table 3. An alignment between how learners prepared for mathematics assessment and how learners perceived their teachers to explain mathematics can be seen as a shared purpose and goal. Yet, an over-emphasis of the B quadrant can detract from thinking modes in the A, C and D quadrants.

Considering that a B-quadrant focus is on skills and procedural knowledge, as indicated in the comprehensive mathematics-specific Whole Brain® Model in Figure 3, learners who over-focus on the B quadrant could be hampered in their development of conceptual knowledge. Their development towards a meta-cognitive understanding will, therefore, also be impeded.

Qualitative Findings and Reflections

The following reflections are a result of both my own scholarly reflexive practice as well as that of the teacher participants. Reflection on one's reflexive practice is in general considered to be meta-reflection, but in the context of the study, specifically Whole Brain® meta-reflection. Moreover, I consider Whole Brain® as both a product and an objective of the research, not only for myself, but also for the teacher participants.

From the reflexive discussions with the teacher participants, it became evident that the degree to which the research influenced each participant's practice was dependent on each teacher's level of professional development. The two teacher participants engaged in post-graduate studies at the time showed the ability to complement their "existing competencies with needed situational competencies" (Herrmann, 1996:39), meaning that these teachers were not limited by their thinking preferences, but were able to employ lesser preferred preferences when needed.

Teacher participants noted that knowledge of Herrmann's Whole Brain® theory initiated an interest in them to explore different strategies with regard to facilitating and assessing learning. One of the participants expressed that "*knowing about HBDI® and being constantly aware of it has made the process of preparation of lessons and assessments far more interesting and has forced me to work differently (and harder!) but it has only improved those processes for me*." Another participant stated that "*exposure to HBDI® has made me aware of the fact that I have to make an effort to access different learning styles that learners relate to*."

The HBDI® is not a personality indicator, and therefore not an indicator of how a teacher would teach. The HBDI® gives insight into thinking and learning preferences involved in a teacher's planning and possibly their emphasis, but cannot be directly correlated to their way of facilitating learning or classroom practice. Since each teacher participant's preferences greatly differed from those of the others, one can conclude that a typical HBDI® profile does not exist for mathematics teachers. The eight teacher participants' individual HBDI® profiles are presented in Figure 6 and a summary of the participants' HBDI® profile scores is presented in Table 1.

The teacher-participant group tested with a fairly balanced Whole Brain® team profile, as is clear from Figure 10, which indicates the participants' collective HBDI® scores as well as their collective adjective pair scores. Although a Whole Brain® teaching team can bring different perspectives to the planning of learning and assessment opportunities, it also has the potential for conflict. During the reflexive discussions, participants with C- and D-quadrant profile preferences indicated that they felt stifled by members of the team who had A- and B-quadrant preferences congruent with more traditional approaches of facilitating learning and assessment in mathematics. One participant said: "*I do find myself in conflict with staff members who have a different profile to me. Being imaginative and intuitive, means I sometimes clash with people more conservative.*"

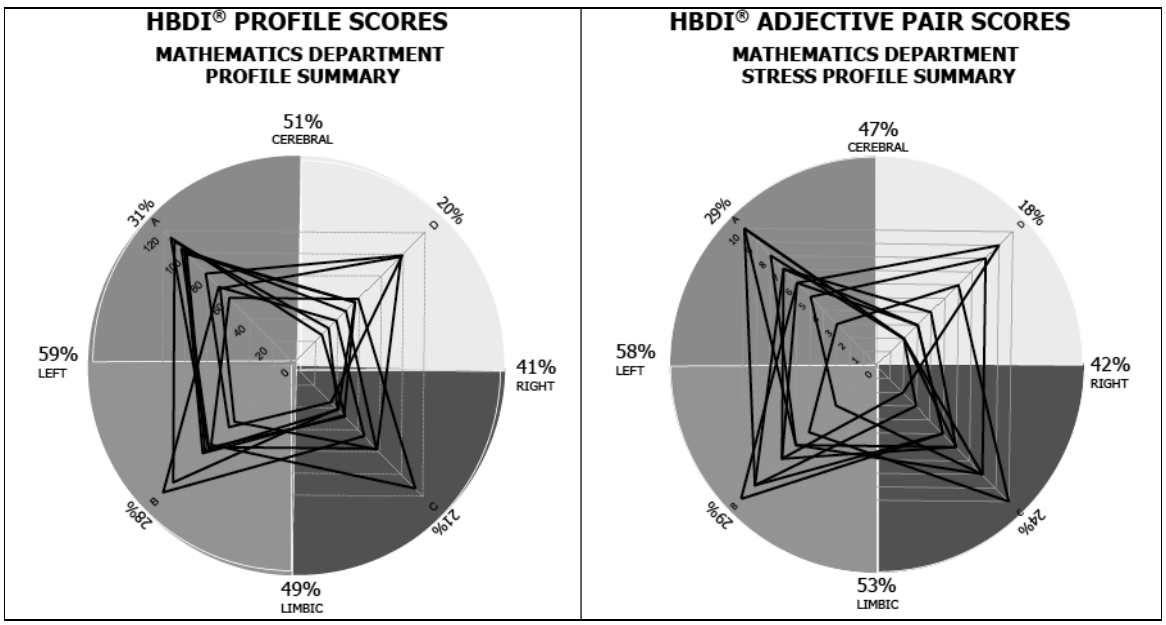


Figure 10 Composite profile scores compared to the teacher participants' adjective pair scores (Randewijk, 2019:189)

A teacher's profile is not necessarily indicative of a teacher's teaching style. The results of the learner questionnaires on what learners perceived their teachers to do that was beneficial to their learning indicate that for three of the teacher participants, as well as myself, preferences for the quadrants were similar to each teachers' HBDI® adjective pair score (or stress profile). According to their learners, these four teachers displayed actions in accordance with thinking modes that the learners deemed important when faced with certain classroom pressures or constraints. Their teaching styles, according to learners, was more aligned to their HBDI® adjective pair scores (or stress profile) than to their HBDI® scores.

According to Hattie and Yates (2013) the most valuable indicator of learners' success is the feedback they receive from their teachers. Yet, only one of the teacher participants intentionally emphasised that learners should analyse their incorrect answers to assessments and class activities. By drawing learners' attention to the methods they use, teachers can help learners think about their thinking, therefore, aiding their engagement in metacognition.

Each HBDI® descriptor can be viewed negatively and positively, which means that one's strength can also be one's weakness. One of the participants chose the key descriptor of "*emotional*" when completing the HBDI® questionnaire. Although it seems to be a descriptor with a negative connotation, viewing it in terms of involvement and support provides a completely different view of the descriptor. The participant stated:

> *I believe the emotional value can be both negative and positive when it comes to teaching. I share the experiences with my learners, I try to keep them motivated and I console them when they are upset and down. However, due to my emotions I can also overreact. I do, however, believe that any key descriptor can have both a positive and negative quality.*

Discussions on the duality of descriptors aided participants in metacognitive self-awareness. This self-awareness was both an intention and a result of this action research in line with McTaggart (1994:317) who describes action research as "a form of self-reflective enquiry" within a collaborative setting to improve personal reflexive practice.

One of the teacher participants noted that being self-aware was important in maintaining a balanced approach to facilitating learning and that a focus skewed towards any of the four quadrants could create weaknesses in the remaining quadrants. It can also help to alleviate anxiety, as an over-focus on specifically the C quadrant can become exhaustive in a teaching setting. As the participant expressed: "*I think that sometimes I get burnt out because I give so much of myself. I sometimes need to take a step back and say no.*"

This self-awareness is indicative of teachers who are reflexive of their practice as a result of their knowledge of the HBDI®. This self-awareness and reflection on practice, as initiated by the HBDI®, was considered to be one of the objectives of the research.

Conclusion and Recommendations

The literature review, along with the research findings, supports the view that there is a need for a Whole Brain® approach to facilitating learning and assessment in mathematics. Therefore, in order to address the first research question, I situated the seminal constructivist and psycho-mathematical theories within Herrmann's Whole Brain® quadrant structure and extrapolated on these theories from the reflexive action research findings of this study. This comprehensive mathematics-specific Whole Brain® Model is proposed as a framework for planning learning opportunities in mathematics and aims to add to the body of knowledge regarding the facilitation and assessment of mathematics at Senior Phase level. It is further proposed that a comprehensive subject-specific Whole Brain® Model is constructed in other learning areas or subjects in order to facilitate a Whole Brain® approach to learning. However, further research is needed to determine the practicality of the use of the model as this research focused on the design of the model rather than its application.

Furthermore, the use of the HBDI® is indicated as an instrument for initiating metacognitive reflexive practice, more specifically, Whole Brain® metacognition, which is also an objective of the mathematics-specific Whole Brain® Model. The use of the HBDI® in an independent school where professional development is highly valued, aided the manner in which teacher participants responded to the research. Yet, the HBDI® has shown to be effective in a variety of settings (Herrmann, 1995) and this study adds support to that finding. It is further proposed that the HBDI® is used for teacher professional development within a school environment where professional development is not as highly valued in order to determine the degree to which reflexive practice is initiated through the use of the instrument. With both time and monetary constraints in many South African schools, this endeavour could prove problematic.

Conducting the research in a well-resourced independent school in South Africa, which is less affected by socio-economic pressures, assisted in initiating reflexive practice among mathematics teachers. The findings of this study may, therefore, also be applicable to mathematics teaching teams outside of South Africa while at the same time, providing insight into facilitating mathematics learning of the South African mathematics curriculum.

Authors' Contributions

The first (corresponding) author conceptualised and drafted the article and in collaboration with the second author, gathered the quantitative and qualitative data and designed Figures 2, 3 and 4. All authors continually reviewed the manuscript and did language editing up to the submission stage. The second and third authors contributed in a supervisory role, reviewing all stages and aspects of the study. All authors reviewed the final manuscript.

Notes

i. The Senior Phase in the South African schooling system refers to Grades 7, 8 and 9, which includes learners between the ages of 12 and 15.

ii. The first author conceptualised and conducted the study while the second and third authors assisted in co-monitoring the process. As the project was of self-reflexive nature, the article is written in the first person.
iii. This article is based on the doctoral thesis of Elmarie Randewijk.

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