A Feasibility Study in an Intervention Program to support Improvement in the Working Memory of Deaf Children

A study submitted in partial fulfilment of the requirements for the degree of Master of Arts of the University of Hertfordshire

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BATOD	British Association for Teachers of Deaf Children and Young People
BDSp	Backward Digit Span
BSL	British Sign Language
CBTT	Corsi Block Tapping Test
CE	Central Executive
DL	D/deaf Learner
DLs	D/deaf Learners
EF	Executive Functioning
FDSp	Forward Digit Span
HL	Hearing Learner
HLs	Hearing Learners
LTM	Long Term Memory
PL	Phonological Loop
QToD	Qualified Teacher of the Deaf
QToDs	Qualified Teachers of the Deaf
STM	Short Term Memory
VSSP	Visuospatial Sketchpad
WM	Working Memory

Abstract

Working memory is the part of the brain that allows us to store attended information for manipulation. This manipulation allows us to learn. D/deaf learners *generally* exhibit weaker working memory. Since working memory is essential to learning, D/deaf learners often have delays in learning. ***Objectives:*** To evaluate the effectiveness of an intervention programme on D/deaf learners' performance on memory tasks. ***Methods:*** Thirty-three D/deaf learners between the ages of 12 to 18 years with moderate, severe, and profound hearing loss completed the study. They were assessed using the Forward Digit Span, Backward Digit Span, and the Corsi Forward Block Tapping Test. An intervention programme consisting of independent computer-based activities and teacher-led activities was regularly administered in their mathematics lessons, lasting a total of one hour each week over a ten-week period. At the end of the intervention programme, they were reassessed, and the post scores were recorded. ***Results:*** The results showed a significant difference between the learners' pre- and post-test scores in the Forward and Backward Digit Span with small effect sizes (Cohen's d = 0.309 and 0.429). The improvement in scores for the Corsi Forward Block Tapping Test was also significant, with a medium effect size (Cohen's d = 0.581). ***Conclusions:*** The intervention programme demonstrated that memory training activities can enhance D/deaf learners' working memory. However, it is important to note that the sample size was small (N = 33), and the intervention programme performed over a short 10-week period. Further tests are required with larger sample sizes over a longer period, to determine the intervention programme's long-term effect.

1. D/deaf Children and Mathematics

1.1 Performance of D/deaf Learners in Maths

D/deaf learners (DLs) consistently underperform in mathematics compared to hearing learners (HLs). The Education Policy Institute (Hutchinson, 2023) published a report that compared the attainment of DLs and HLs in mathematics *and* English in 2019. It showed that for learners aged 7 years, the attainment of DLs was 8.8 months behind HLs, increasing to 17.5 months for learners aged 16. The results of GCSE examinations showed that DLs' attainment was on average 1.3 grades behind HLs.

A more recent report by the NDCS (2024), analysed government data collected in 2024. It compared the difference between the proportion of DLs, and the proportion of all learners achieving the expected standards. They found that the proportion of DLs achieving the expected standard was lower. This gap was 29% in the Early Years Learning Goals (from birth to the age of 5) (DfE, 2024a), particularly in numbers (25%) and number patterns (27%) in the 17 Early Learning Goals. In Year 4 (between the ages of 8 and 9), the gap was 7% in the 'Multiplication Table Skills' (DfE, 2024b), and at the end of Key Stage 2 (between the ages of 10 and 11), the gap in mathematics was 21% (DfE, 2024c). This report also showed that the gap in achieving a grade 5 and above in GCSE mathematics *and* English was 26% (DfE, 2024d).

D/deaf learners face challenges in many areas of mathematics. These include difficulties with multiplicative reasoning (Nunes et al., 2009), understanding inverse relations (Nunes et al., 2008), working with fractions (Mousley and Kurz, 2015), and solving story problems (Kritzer, 2009). These areas of difficulty highlight the need for targeted interventions and teaching strategies to support DLs. While there are many reasons contributing to the underachievement of DLs, they can be summarised into three principal areas: incidental learning, language proficiency, and working memory (WM).

1.2 Barriers to improving Mathematics

The first reason is the lack of **incidental learning**. Defined as unplanned or unintended learning that occurs naturally in everyday situations (Kelly, 2012), this is something that is often intuitive and spontaneous to most HLs. Learning starts early, and young learners often acquire their first mathematical ideas through informal learning and experiences (Barbosa, 2014). Hearing learners often overhear conversations, observe simple mathematical concepts, experience and discuss sequences of activities in life. The opposite is true for DLs, who, unless taught directly, may miss these opportunities, especially with more mathematical concepts (Kritzer, 2009).

To support DLs in overcoming these barriers, early interventions need to be set up to ensure they are exposed to a wide variety of topics. Pagliaro and Kritzer (2013) and Kramer and Grote (2009) both emphasise the importance of teaching mathematical concepts early to young learners, particularly in areas such as time and sequencing, while integrating mathematical language. Parents and carers, especially during preschool, can play a crucial role in helping to reduce deficits caused by the lack of incidental learning. To support parents and carers, intervention programmes have been developed to provide them with strategies that can help their child's mathematical development (Kritzer and Pagliaro, 2013).

The second reason is low **language proficiency**. Language skills are essential for understanding and explaining mathematical concepts, as they are needed to articulate and understand mathematical ideas (Edwards, Edwards, and Langdon, 2013; Kritzer, 2009). Without these skills, DLs cannot solve mathematics problems. As DLs progress through their education, the complexity of the language required to explain more advanced mathematical concepts also increases. This could help explain why the attainment gap between DLs and HLs tends to widen from the age of 5 to 14 (NDCS, 2024). To support them in overcoming these challenges, it is important to adapt and modify instructions and questions. These might include simplifying language by using shorter sentences and fewer words, incorporating visual aids such as diagrams to clarify concepts, presenting word problems in multiple ways to ensure accessibility and understanding (Meadow-Orlans, Spencer, and Koester, 2015), and using kinaesthetic methods (Marschark and Hauser, 2012). These strategies can provide DLs with the tools they need to help them bridge the gap and overcome these barriers.

The third reason is weak **working memory (WM)**. Working memory is important in a learner's ability to receive and retain information in the short-term memory (STM). When it is retained, it is organised and manipulated (Baddeley, 2010; Beer et al., 2010; Cowan, 2014). One could argue that without WM, learning cannot take place (Alloway, 2011; Passolunghi and Lanfranchi, 2012). Working memory for all learners, D/deaf and hearing, has been strongly associated with the core subjects; it is essential for reading and writing (Kronenberger et al., 2010), and learning mathematics (De Smedt et al., 2009).

A DL with weak WM will likely have difficulties learning (Gathercole et al., 2016), especially in word problems (Alloway and Passolounghi, 2011), calculations (Bull and Scerif, 2001), and problem solving (David, 2012). Working memory skills also strongly predict academic achievement in mathematics in DLs (Geary et al., 2007; Gottardis, Nunes, and Lunt, 2011; Lang and Pagliaro, 2007). Since DLs generally have weaker WM than HLs (Harris and Moreno, 2004; Pisoni, 2008), it is perhaps not surprising that they often face many difficulties and challenges in learning mathematics.

2. D/deaf Children and Working Memory

2.1 Baddeley's Model

To understand why DLs tend to have weaker WM, it is necessary to understand its structure. The most widely accepted model was first put forward by Baddeley and Hitch (1974). They modified the existing multi-store model by Atkinson and Shiffrin (1968), consisting of a STM component that stored both auditory and visual-spatial information. Baddeley and Hitch's model (1974) consisted of three distinct components: the visuospatial sketchpad (VSSP), phonological loop (PL), and central executive (CE). Later, Baddeley (2000, 2010) added another component called the episodic buffer. Each of these components serves a unique function within the model (Figure 1). Evidence of the existence of separate auditory and visual storage components can be explained by observations seen in the notable case of patient KF who experienced damage to the brain following a motorcycle accident. After the accident, he had difficulties processing verbal information, but his visual memory seemed to be intact (Shallice and Warrington, 1977). This demonstrated that the two components were independent.

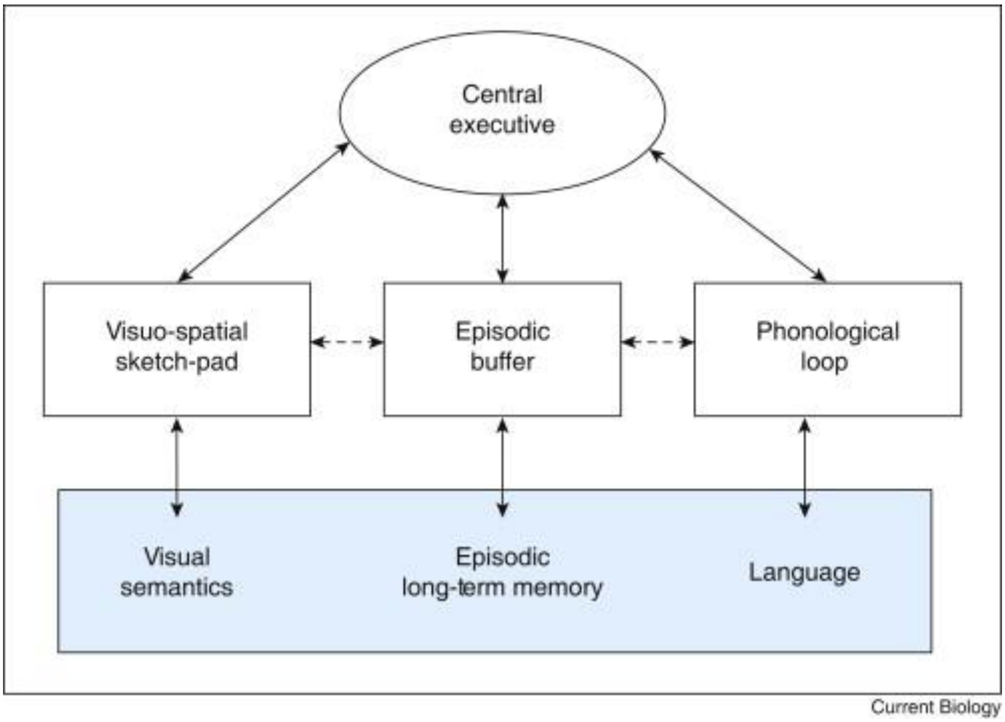

Figure 1. *Baddeley's Model of Working Memory (Baddeley, 2010)*

Baddeley's model (1974, 2000) has been around for many years, and with the increasing improvements in technology, newer 'state-based' models are beginning to take prominence. They suggest that WM results from temporarily increasing attention to representations that already exist in parts of the memory (Cowan, 1995; Oberauer, 2002), with evidence from research using fMRI data (Lewis-Peacock and Postle, 2012). Even with these latest developments, the half-century-old model by Baddeley and Hitch (1974), and Baddeley (2010) is still important in WM research. Evidence-based research pertaining to the WM model by Baddeley (2000), as of 2006, is the most cited theory (Leffard et al., 2006). Hence, throughout the rest of this study, references will be made to this model.

To understand why DLs have weaker WM, an understanding of how each component works is required. The role of the episodic buffer that links the long-term memory (LTM) with the other three components will not be discussed in detail, as it will not be the focus of the intervention.

2.2 The Phonological Loop

The phonological loop (PL) exists to retain information sourced by auditory means. It is responsible for storing limited verbal information by recording speech sounds in their temporal order. Information stored can be rehearsed through articulatory repetition (known as the inner voice) which allows information to be retained for longer, preventing it from decaying.

D/deaf learners, on average, have weaker auditory information going through the PL than HLs. If this continues over an extended period, and little support is given to boost these auditory signals, they will be at risk of developing difficulties in processing them. This process is called *auditory deprivation*, where disrupted auditory signals to the brain lead to problems processing sound. This process can cause parts of the brain to experience atrophy, resulting in regions usually responsible for hearing being 'reorganised' to strengthen the other senses (Bavelier, Dye, and Hauser, 2006; Campbell and Sharma, 2014; Glick and Sharma, 2017; Kleinjung and Moller, 2024; Vachon et al., 2013). While this synaptic pruning of unused neurons and synapses in the brain can lead to improved peripheral vision, as seen in reaction time experiments (Codina et al., 2017), it can also lead to difficulties in sequencing information and temporal tasks (Burkholder and Pisoni, 2006; Cormier et al., 2012; Hamilton, 2011; Pisoni et al., 2010) leading to an overall weakening of their STM (Dawson et al., 2002). Ineffective rehearsal or refreshing mechanisms caused by the weakened ability to store temporal information (Burkholder and Pisoni, 2003) can lead to problems in retaining verbal information in the PL (Pisoni and Cleary, 2003; Geers et al., 2011). Subsequently, it can lead to difficulties in language, including reading skills (Geers, 2003), and poor expressive skills (Harris et al., 2013).

From a mathematical point of view, this could potentially lead to DLs having problems retaining information mentally, causing difficulties in mental arithmetic tasks such as counting. They might also have difficulties sequencing events, especially of a temporal nature, so often display problems with ordering and timing activities. Simple strategies can be used to support DLs in keeping track of information due to a weaker PL. These can include counting with fingers or blocks (Geary, 2004), using memory aids (Gathercole and Alloway, 2004), and other techniques such as ‘cognitive off-loading’ involving the use of calculators and notepads (Berry et al., 2019).

Native Deaf Learners raised with **sign language** are an exception. It has been demonstrated that they have similar WM capacities to HLs (Boutla et al., 2004; Rudner, Andin, and Rönnberg, 2009). Explaining this is difficult using the model by Baddeley (2000), however, using more recent techniques such as fMRI imaging (MacSweeney et al., 2008), and analysis of medical records of brain-damaged patients (Corina and Knapp, 2006), may help to provide alternative explanations. MacSweeney et al., (2008) and Rönnberg, Soderfeldt and Risberg (2000) showed that native signers, and learners using spoken language have similar neurological structures in the left-hand side of the brain, suggesting that deafness itself may not be the cause of an overall weakened WM, but rather the lack of language input.

2.3 The Visuospatial Sketchpad

The visuospatial sketchpad (VSSP) is a storage component that retains limited information sourced by visual and spatial means. D/deaf learners without additional visual difficulties (for example, Usher's Syndrome), where unhindered information goes to the VSSP, should in theory, perform similarly to HLs.

In tasks that assess *simultaneous* presentation of visual information (Arnold and Mills, 2001; Pisoni and Cleary, 2003; Zarfaty, Nunes, and Bryant, 2004), both HLs and DLs performed similarly. However, native sign language users often outperform non-signers, including HLs and other DLs (Hall and Bavelier, 2010), so DLs are, *in general*, as good, if not better, than HLs at visuospatial tests involving *simultaneous* presentation. The *sequencing* of visual information tells a slightly different story. While the visual information is managed by the VSSP, the sequencing aspect is often overseen by the CE which is linked to planning and management (and will be discussed later). Since the CE is often weaker in DLs than in HLs, it is not surprising that DLs often perform worse in *sequencing* visual information than in *simultaneous* tasks (Zarfaty, Nunes, and Bryant, 2004). In fact, some studies involving DLs with a weakened CE, showed they performed lower than HLs in the visuospatial tasks (Stiles, McGregor, and Bentler, 2012).

From a mathematical viewpoint, we can use the visuospatial strengths of DLs to support their language difficulties and general understanding. Visual diagrams can be used to minimise words (Crisp, 2015), link words to pictorial diagrams (Lund and Douglas, 2016), and link words to real images (Lang and Pagliaro, 2007).

2.4 The Central Executive

The last component of the WM is called the **central executive** (CE). This component allows for the coordination of verbal and visuospatial information for organisation and usage. Unlike the VSSP and the PL, which are dedicated storage systems, the CE is quite different as the aim is to control processes in the WM (Baddeley, 2010). It covers many areas, including attention, inhibition, planning, and problem solving (Nyongesa et al., 2019), and the skills used to achieve those tasks are known as executive function (EF) skills.

D/deaf learners regularly perform poorly in tests of EF (Charry-Sanchez et al., 2022; Hintermair, 2013; Kronenberger et al., 2014). Unlike the area of research around the PL, not much is known about the causes, however, it is thought that language deprivation may play a crucial part (Hall et al., 2018). Since the CE is key to planning, organising, and problem solving (Botting et al., 2017; Harris and Moreno, 2004), this can lead to problems in mathematics, as the use of EF is essential (De Corte et al., 2011). However, EFs are not fixed and can be taught with the right strategies (Clements, Sarama, and Germeroth, 2016) and training methods (Nunes et al., 2012), suggesting that improvements can be made.

2.5 The Intervention Programme

This study proposes an intervention programme aimed at improving the WM of DLs, specifically targeting the PL, VSSP, and CE. This is important, as WM is crucial to the learning of mathematics. The motivation to develop this intervention programme is based on the study by Nunes et al. (2012) and the NDCS (2012). Their aim was to support young learners to develop their WM by improving their rehearsal strategies and attention. With some similarities and differences to their study, the current study looks at, firstly, improving the recall of span length in the PL by enhancing rehearsal processes. It will also aim to enhance their ability to locate items through tasks that train the VSSP. Finally, it will target the CE by training DLs to hold and rearrange information in their minds. As a side effect, it will also train their attention and inhibition skills, which are central to EF. The following hypotheses will be used to assess the WM of DLs:

H_0: There is *no* significant difference in the mean scores of the working memory tests:

(i) FDSp (Hypothesis 1)

(ii) BDSp (Hypothesis 2)

(iii) CBTT (Hypothesis 3)

from pre- to post-tests of D/deaf learners between the ages of 12 and 18 who complete the intervention programme.

H_1: There will be a significant *increase* in the mean scores of the working memory tests:

(i) FDSp (Hypothesis 1)

(ii) BDSp (Hypothesis 2)

(iii) CBTT (Hypothesis 3)

from pre- to post-tests of D/deaf learners between the ages of 12 and 18 who complete the intervention programme.

Since the intervention will be conducted over a ten-week period and achievement will be determined using test scores, the independent variable will be time, and the dependent variables will be the pre- and post-test mean scores of the WM tests. The test statistic to be used is one-tailed, as the alternative hypotheses (H_1) expects significant *increases* in WM scores.

3. Methodology

3.1 Research Design

This study employed a pre- and post-test design. A **quantitative design** was chosen, as the aim was to collect primary data, apply statistical methods, and draw conclusions (Schweigert, 2021). A strength of this method is that statistical analysis is objective and rational (Denscombe, 2010) allowing researchers to replicate and generalise results to larger populations (Steckler et al., 1992). However, it can lack the depth of detail provided by an 'explorative' approach, as seen in a qualitative design (Tracey, 2013). Incorporating both into a mixed-methods design would be ideal, but due to time and work constraints, this approach was impractical. Three different approaches were considered: an independent design, a matched participants design, and a repeated measures design (McLeod, 2023).

The **independent design** was ruled out due to the small number of DLs available. With only 33 involved, three groups of 11 DLs would have been required for each of the assessments. With such small groups, any results calculated could be disproportionately skewed, as the mean (in calculations performed later) is sensitive to outliers (Manikandan, 2011).

The **matched participants design** was also ruled out. In addition to the small number of DLs available, it would have been difficult to match them effectively. In this design, they are paired based on similar variables within the independent design. However, due to the heterogeneous nature of DLs, matching them would be challenging. Deafness can stem from various aetiologies and causes (biological and environmental) (Kochhar, Hildebrand, and Smith, 2007) leading to many different hearing levels and experiences. The type of amplification used (if any), date of adoption, and habit of use, have far-reaching implications on DLs' hearing levels, language levels, and subsequent educational achievements (Matte-Landy et al., 2020). Considering all these factors, meaningful matching of DLs would have been very difficult.

3.2 Repeated Measures, Advantages and Disadvantages

A pre-post **repeated-measures design** was therefore chosen. In this design, all the learners participated in all the tests, reducing the need for a larger sample size. By using the same group of learners, we can control for their individual differences. However, with this method, there are some factors that could negatively influence the results, including history, maturity, order effects, and carryover effects (McLeod, 2023). To mitigate these, the structure needed to be considered.

As the intervention programme was conducted over a ten-week period, there were concerns that natural **maturation** could inflate the results. Research by Brockmole and Logie (2013) involving a large data set of 55753 people between the ages of 8 and 75, found that people naturally improve their visual memory up to the age of 20 before a sharp decline begins. They assessed them on identifying the colour, object, and position of shapes. Using their results (Figure 2), and modelling with a linear trendline, we can see that between the ages of 12 and 18 (the age range of the DLs in the current study), the mean score increased (the number of trials correct) by approximately one-third of a trial per year. Over a ten-week period (the length of the current intervention), this translates to a small, expected improvement of around 0.06 trials, or 6% of a trial.

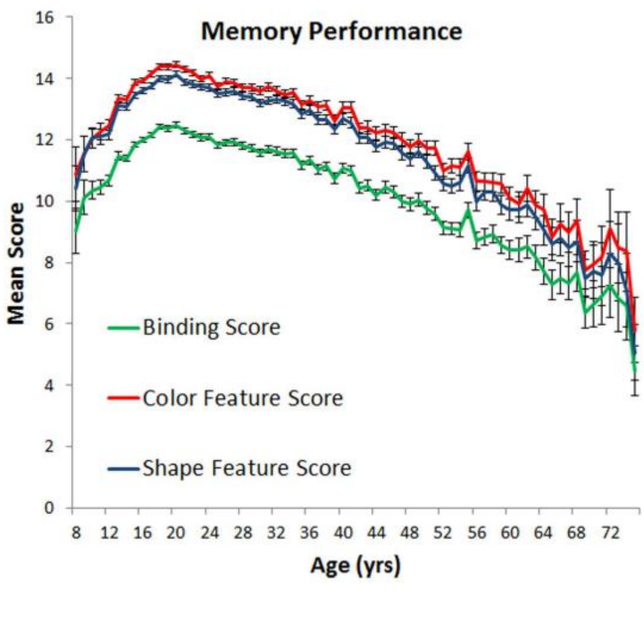

Figure 2. *Mean objects remembered as a function of age (Brockmole and Logie, 2013, p. 3)*

Even though hearing status was not factored into their research, we can use ONS (2015) data for the year 2014 to find a rough percentage of D/deaf people. It showed that there were around 387500 adults (0.006%) aged between 18 and 80 in the UK population with severe to profound deafness. This translates to their study having approximately 334 severe to profound D/deaf people - a very small number. Since DLs tend to have weaker WM than the HLs, we can assume that based on this data, maturation is even *less* likely to make any meaningful changes to our post-intervention scores.

D'Antuono et al. (2020) supported the findings by Brockmole and Logie (2013). Using the Corsi Block Tapping Test, a test of visual WM, they showed a slight decline in the span recall between the age groups of 15 - 20, and 21 - 35 years, from around 5.5 to 5.4 spans. This small difference is unlikely to affect the results of the older DLs in the current study. Their findings on the Forward Digit Span and Backward Digit Span, tests for the PL and the CE respectively, also indicated small, age-dependent improvements of about 0.2 and 0.3 spans between the same groups. Therefore, it can be assumed that improvement in WM due to maturation will be minimal over the 10-week period of our intervention.

Another consideration is that in the *verbal* test, the **same questions** are used in the pre- *and* post-tests. While DLs may remember some of the questions from the pre-test while performing their post-test, it is unlikely, as the two tests were conducted 10 weeks apart. In the *visual* test, 500 randomised patterns were used, making it unlikely the DLs would encounter the same one, thus reducing the practice effect: the repeated exposure to a task that can lead to false improvements (Bartels et al., 2010).

The pre- and post-tests were largely conducted on Mondays, between late morning and lunchtime, and on Tuesday and Wednesday mornings before lunch. These times were chosen, as assessing the learners later in the day, especially in the afternoon, can reduce performance (Sjosten-Bell, 2005; Wise, Kuhfeld, and Linder, 2024). Tests were not performed early on Monday mornings, as observations made by the QToD showed that the DLs seemed to be more tired after the weekend.

To **counterbalance** the order of tests, half of the DLs started with the verbal test, and half with the visual. Within the verbal tests, the Forward Digit Span was always conducted before the Backward Digit Span, following their standardised protocol. This order also has benefits; explaining instructions on how to answer the BDSp questions were easier once they have completed the FDSp. This helped reduce the practice effect by unnecessarily providing the DLs with too many pre-test examples.

3.3 Participants

Before beginning, it was important to know the minimum number of DLs to recruit. This was calculated using the software G*Power version 3.1.9.7 (Faul et al., 2007). Using Cohen's *d* value from the intervention programme by Nunes et al. (2012), the value of $d = 0.78$ was entered into the software. With a significance criterion of $\alpha = 0.05$, and power = 0.95, the minimum sample size determined was $N = 20$. It is important to note that even though the value of $d = 0.78$ was used in the current study, both studies focused on slightly different areas. However, there is limited research in this area, so the value of $d = 0.78$ provided by Nunes et al. (2012) is still the best estimate to use.

The study was conducted at a special school for the Deaf in the south of England. To be a part of the study, two eligibility criteria needed to be met:

1. The DLs chosen for the intervention needed to be able to take part in the assessments and activities.
2. The DLs were also required to participate in at least 80% of the activities, to ensure they received enough practice.

Since the study took place during their regular mathematics lessons, those not included in the study could still take part in the activities, but their test scores were not included in the analysis. The DLs were recruited through convenience sampling from their mathematics groups. While convenience sampling is sometimes criticised as being 'not credible' (Tracey, 2013), it was appropriate for this intervention study, as the sample of DLs recruited from the classes all demonstrate the criteria that were needed; they needed to be D/deaf and learning mathematics.

3.4 Administration of the Tests

The pre-tests were delivered by *one* qualified Teacher of the Deaf (QToD) to ensure consistency in dissemination. They took place in a quiet, tidy, and non-distracting room familiar to the DLs. The QToD was experienced in communication with DLs and was skilled in using speech, British sign language (BSL), and sign supported English (SSE). This allowed him to use the most appropriate mode of communication for each DL, so he could support them, and address any misunderstandings, issues, and concerns.

As touched upon briefly in section 3.2, the DLs were required to complete three pre-tests: the Forward Digit Span (FDSp), Backward Digit Span (BDSp), and the Corsi Block Tapping Test (CBTT). These tests were chosen to measure their PL, CE, and VSSP. The questions for the FDSp and the BDSp were from a standardised assessment package, and the CBTT, from a trusted website with psychological and cognitive tools, which will be explained in more detail in section 3.5.

Considerations were taken before the tests were administered. The FDSp and BDSp were delivered as closely as possible to the instructions outlined in the test manual, but adjustments were needed; sign language was used with the spoken instructions, and these were regularly modified to ensure the learners fully understood the tasks. Since the test was not administered exactly as in the manual, scaled scores and normative data were not used. This did not affect the study, as the aim was to compare the pre- and post-test scores and not compare them with the wider population. For the CBTT, the manualised instructions displayed were followed.

Setting up the environment for FDSp and BDSp assessments included seating the DLs *opposite* the QToD, approximately one metre apart, with a table placed between them. For the CBTT, the DL was seated *next to* the QToD, so that both could see the tablet that was being used. The QToD was always seated in a position where his back was not facing bright lights and wore plain dark clothing to ensure the sign language and non-manual features were seen clearly. This was important, as the communication between the QToD and DLs needed to be clear, as mistakes could bias the scores collected.

All DLs who used listening equipment had it checked using the six Ling Sounds (Ling, 2002) to make sure it was working normally. For those who relied on speech and listening to communicate, a soundfield system made up of a Phonak DigiMaster 5000 (Roger, 2025a) connected to a Phonak Roger Inspiro (Roger, 2025b) was used.

3.5 Assessments of Working Memory

3.5.1 Forward Digit Span Administration

The FDSp is a standard test used to assess verbal WM (Elliot and Smith, 2011; Wechsler, 2014). The aim is to measure the number of digits a learner can recall while using vocal or subvocal rehearsal strategies (Acheson and MacDonald, 2009; Baddeley, 2012; Gathercole et al., 2004). The questions used in this study are from the Wechsler Intelligence Scale for Children, Fifth Edition (WISC-V) (Na and Burns, 2016; Wechsler, 2014) and are frequently used by psychologists (Piotrowski, 2017; Rabin, Paolillo, and Barr, 2016). The WISC-V is known for its high reliability of 0.81 (Farmer and Kim, 2020) and is widely used to assess a learner's intellectual ability by generating a full-scale IQ score. It is also useful in predicting mathematical performance (Gygi et al., 2017). It is important to note that even though the WISC-V (Wechsler, 2014) is designed for young learners between the ages of 6 and 16, it was also used with learners aged up to 18 years, due to their developmental abilities matching that age group.

The FDSp test consists of nine rounds, each with two sequences containing the digits from 1 to 9. In the first round, the learner must recall two two-digit sequences. If one or both sequences are correctly recalled, they proceed to the next round, where the process is repeated with a sequence one digit longer than before. This continues until the learner makes mistakes in both sequences within a single round, or until the whole test is completed.

The test was administered to the DLs, and the total score and longest span were recorded (appendix ix): the total score representing the number of sequences recalled correctly, and the longest span representing the number of digits in the longest recalled sequence.

3.5.2 Backward Digit Span Administration

The BDSp is used to assess parts of the WM, particularly the CE. This test is more complex than the FDSp, as learners are required not only to recall a sequence of digits, but to mentally reorganise them. For some learners, they may even use visual imagery to support their recall (Flanagan and Kaufman, 2009; Groth-Marnat, 2009; Wechsler, 2014).

Like the FDSp, the BDSp questions used in this study are from the WISC-V (Na and Burns, 2016; Wechsler, 2014). The structure and procedure are very similar to the FDSp, except for two differences: the inclusion of additional practice questions at the start of the test to help the learners build their confidence, and the requirement for the sequences to be repeated in reverse order.

In the current study, the two practice questions were given before the main test was administered. At the end of the test, the total score and longest span length were recorded for each DL (appendix x). There were two DLs who needed further clarification of the task, requiring an additional three practice questions. The QToD prepared the sequences (3 – 6), (1 – 8), and (7 – 1) in advance, anticipating that some DLs would need further support. These extra three sequences were different from the test questions.

3.5.3 Corsi Block Tapping Test (Manual)

The CBTT is generally used to assess the VSSP (Corsi, 1972; Milner, 1971; Richardson, 2007). It also engages other parts of the WM, particularly the CE. This test evaluates a learner's ability to recall the position, and order of a sequence of blocks. It was chosen because it is widely used by professionals in psychological tests (Bo, Jennett, and Seidler, 2011; Fischer, 2001) and has good reliability of 0.82 (Siddi et al., 2020). The test is straightforward to understand, administer, and perform.

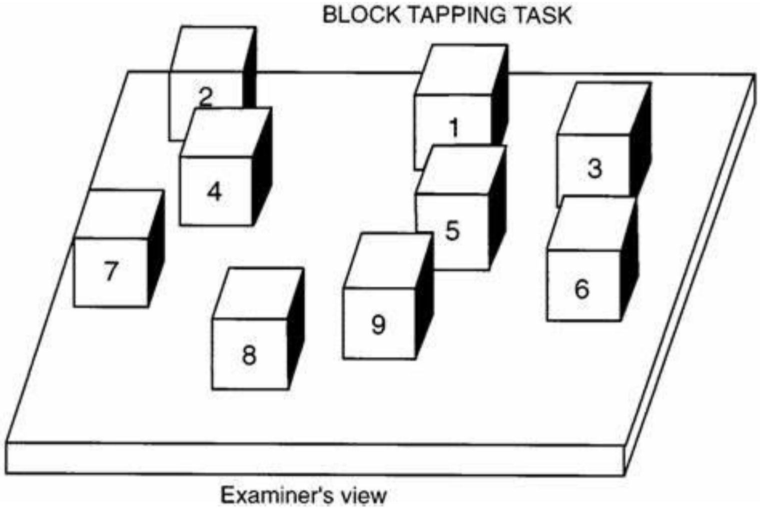

Figure 3. *Corsi Block Tapping Test (Corsi, 1972, p. 37)*

In the original version of the test (Corsi, 1972; Milner, 1971), nine cubical blocks, each with a side length of 1.25 inches, were placed in randomised positions on a board (Figure 3). In the first round, two blocks were tapped by the administrator using a 6-inch stick, and the learner was required to copy the sequence. If it was correctly copied, they progressed to the next round, where the sequence length increased by one. This continued until either the learner made a mistake, or the whole test was completed.

Since its start, the CBTT has been repeated and adapted by many researchers. Berch, Krikorian, and Huha (1998) reviewed 38 studies and found that many had their own standardisations, with differences in structure and methodology. Structural variations included differences in the size and colour of the blocks and the board, the number and placement of blocks, and the scoring procedures. Methodological differences included the rate of tapping, the number of attempts per round, the scoring procedures, and the discontinuance criteria. This variability makes it difficult to compare data across studies. Some researchers have tried to standardise the test, for example, Kessels et al. (2000) who developed a version that addressed many concerns raised by Berch, Krikorian, and Huha (1998).

3.5.4 Corsi Block Tapping Test (Digital)

As technology advanced, digital versions of psychological tests became more common, making them easier to use and manage for clinicians (Rowe, Hasher, and Turcotte, 2008). In addition, the move from manual to digital forms has further complicated standardisation procedures. Physical cubes have been replaced by flat squares, and the tapping of the cubes has been replaced by the clicking (or pressing) of squares. Since these two forms are very different, there have been concerns about the equivalence of them (Brunetti, Del Gatto, and Delogu, 2014). Despite these concerns, research by Nelson, Dickson, and Baños (2000) involving 30 adult learners (15 female, 15 male) found no significant difference in the performance between manual and digital versions of the CBTT when a *non-direct* input device (a mouse) was used. Robinson and Brewer (2016), with 18 male and 42 female learners, similarly showed no significant difference in span length when using *direct* input devices like electronic tablets. Recent research by Siddi et al. (2020) demonstrated that the digital version has good reliability of 0.77.

Not all researchers, however, agree on the equivalency of the manual and digital versions. Claessen, van der Ham, and Zandvoort (2015), in their pilot study with forty university learners (20 male and 20 female), found that the manual version of the forward CBTT was more accurate.

In the three studies mentioned, the sample sizes were quite small, varying from 30 to 60, translating to margins of error between 18% and 13% in their results (calculated using $1 \div \sqrt{N}$ where *N* is the sample size). It is, therefore, important to take that into consideration when interpreting the results.

The CBTT is not the only test that has raised concerns regarding the differences between manual and digital forms. Noyes and Garland (2003) found that learners who completed the ‘Tower of Hanoi’ task on a computer performed faster. They did, however, require more moves compared to the traditional version, suggesting that different strategies may have been used.

Despite the ongoing debate over the use of manual and digital tests, the digital version was *the* version selected for this study. By performing the digital version in both pre- and post-tests, we were unconcerned about the differences between the two versions.

The DLs in this study were also highly engaged with digital technology - this not only helped them increase their enjoyment of the activity, but helped to reduce boredom, which could negatively affect their performance.

3.5.5 Corsi Block Tapping Test (PsyToolkit)

PsyToolkit (Stoet, 2010, 2017) (Figure 4) was selected for this study because it is an accessible internet-based tool that is free to access (as of 10th April 2025), and reliable for administering tests (Kim, Gabriel, and Gygax, 2019). The version was accessed through the website https://www.psytoolkit.org/experiment-library/corsi.html

The sequences generated by PsyToolkit were drawn from a pool of 500 prepared trials, providing a randomised effect. With so many trials, it is unlikely that the same two patterns would appear in subsequent sessions, which is important given the scoring modifications that will be explained later.

The test could be administered independently, with supervision from the QToD. The default colours used in the test were clear and contrasting, and the flashing squares were easily distinguishable. The squares were presented and illuminated for 500 milliseconds, with a time gap of 250 milliseconds, leading to a total time of 750 milliseconds for each new square presentation. This presentation is slightly faster than the standard manual presentation of 1 second (1000 milliseconds) per block (Corsi, 1972; Kessels et al., 2000). An added benefit of the digital method is that the squares were presented at a consistent rate for all learners, which is difficult in the traditional version (Siddi et al., 2020).

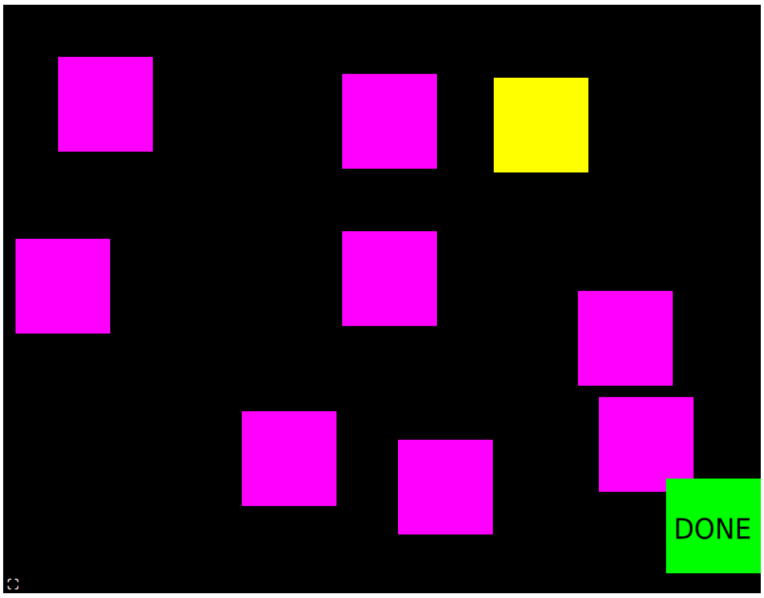

Figure 4. *Corsi Block Tapping Test. Screenshot from PsyToolkit*

At this point, it is important to highlight the differences in scoring between the three assessments. The FDSp and BDSp uses a two-questions-per-round format, whereas the CBTT uses a one-question-per-round format with a retry option for mistakes. The advantage of the two-questions-per-round format is that it allows us not only to determine the longest span but also to assess performance on the shorter sequences. It provides insight into both the span length and the number of mistakes made in earlier rounds. To allow the current study to collect data following the two-questions-per-round format, the CBTT was performed twice. This approach allows for data collection that mirrors the Kessels et al. (2000) normalisation study.

3.5.6 Corsi Block Tapping Test Administration

Before starting, the DLs were checked for sensitivity to flashing lights that could trigger medical reactions. The PsyToolkit CBTT was then loaded onto a 10.1-inch Samsung Galaxy Tab 8+ tablet.

The DLs were given the opportunity to familiarise themselves with the task. At the beginning of the task, they were shown the instruction screen, followed by a countdown and the word ‘GO’. Sign language was used to ensure they understood the instructions. Immediately, nine purple squares appeared, and two of the squares flashed yellow in order. The DLs were then asked to confirm whether they could clearly see the purple squares, the yellow flashing squares, and the green ‘Done’ square.

They were then given opportunities to select the squares by pressing the touchscreen or clicking the mouse. This was important, as they needed ‘hands-on’ experience to help them reduce any performance anxiety. Once they had completed a sequence, they had to press the green ‘DONE’ icon. Immediate feedback was given, showing a red sad face for an incorrect answer, or a happy yellow face for a correct one. The DLs were given the choice to use the touchscreen or a mouse for their pre- and post-tests. They were reminded to select the squares accurately, as mistakes would be recorded as formal answers. They were also told not to ‘double-click’ the mouse or ‘double tap’ the screen as that would select the same square twice.

The default PsyToolkit version of the CBTT was administered twice, and the results were recorded in the two-questions-per-round format. In the first round of the first test, each DL was shown a sequence of two flashing squares. If they correctly copied the sequence, they would move to the next round, with a sequence one square longer. However, if they made a mistake on their first attempt, they were given an opportunity to try another different sequence of the same length. If they answered it correctly, they moved to the next round, otherwise the test would stop. This process was repeated for all rounds. By the end of the test, each DL had likely completed some rounds with a single attempt (correct on the first try) and other rounds with two attempts (incorrect in the first round but correct in the second).

To ensure a complete set of data was collected, a second game was performed focusing on collecting missing data. The DLs who achieved correct answers on their first attempt in the previous game, were given a second sequence to fill in the gaps. In this second sequence, only the first attempt from each round that had been missed previously would be accepted. This approach allowed for a more complete two-questions-per-round set of data. Although a third game may have been required for further rounds, it was not needed. The QToD was aware that there was also a risk that the second test could present sequences already seen in the first game, as the sequences were chosen from a pool of 500. For this reason, the QToD recorded the performance of every DL through the output data provided at the end of each test to ensure that this did not occur (appendix xi).

3.6 The intervention program

Following the completion of pre-tests, the intervention programme was administered. This was a ten-week programme, with one hour allocated each week to develop DLs' WM. Since the DLs had four hourly mathematics lessons weekly, the first 15 minutes of each lesson were dedicated to this programme and the remainder, for the delivery of the normal curriculum. Another idea considered was to have three regular mathematics lessons, followed by a one-hour intervention programme. This was abandoned because consistent practice, which is more spaced out, is often more beneficial than massed practice (Chen et al., 2018).

While the collection of test data was the responsibility of *one* QToD, the class-based intervention activities were delivered by *two*. The intervention programme consisted of three activities: the Number Cards Activity, the Picture Matching Pair Game, and the Simon Game. The Simon Game is the popular STM game, not to be confused with the Simon task (Simon and Wolf, 1963), which assesses stimulus-response compatibility. These activities were chosen as they are designed to target specific components of WM relevant to the skills being assessed. They needed to be different from the activities used in the pre- and post-test tasks, to minimise the potential for practice effects and encourage real improvements in WM abilities.

3.6.1 The Simon Game

The Simon Game, created by Milton Bradley and now distributed by Hasbro, is a game that targets the VSSP by requiring learners to remember the location of flashing lights. It also engages the CE, which is needed to work out the order of the flashing lights and to avoid distractions through improved inhibition. This activity was chosen as it was easily accessible and has been used by researchers to measure and show improvements in learners' WM capacity (Gendle and Ransom, 2006; Parrish et al., 2018; Vignesh Raja et al., 2023).

The digital version of the game consists of a circular plate with four coloured buttons (Figure 5). The goal is to copy an increasingly complex sequence of flashing colours in the same way they were presented. The game ends when the learner makes a mistake.

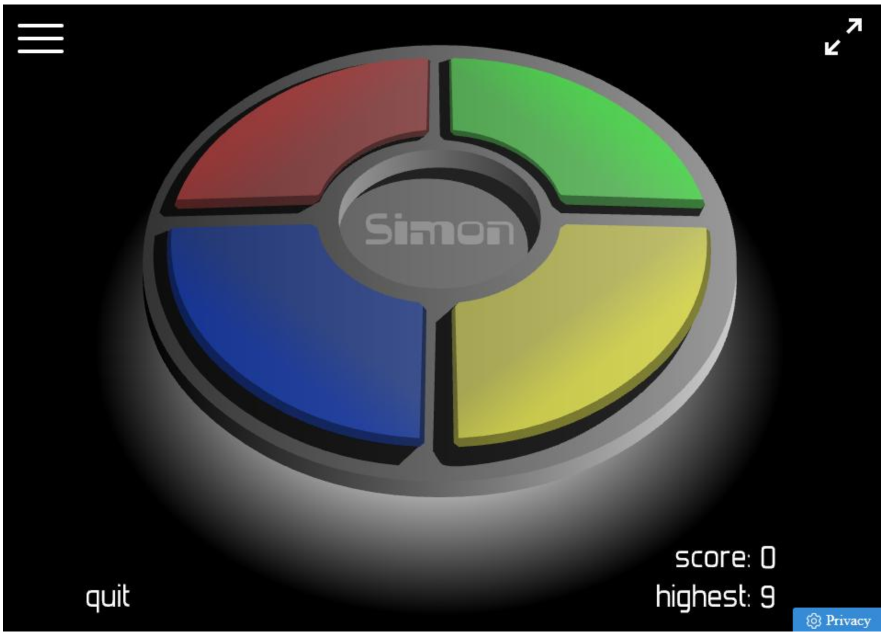

Figure 5. *Simon Game. Screenshot from www.freesimon.org*

In the first round, a single colour flashes, and the learner is required to copy it by tapping the same colour. If performed correctly, they move on to the second round, where two consecutive colours flash - one from the first round, and the new colour from the second (note: two consecutive flashes can be of the same colour). If copied correctly, they progress to the third round, involving three flashes - two from the previous rounds and one new flash. This is repeated, and the game stops when a mistake is made.

The version of the game used in this study was accessible via the website www.freesimon.org. The DLs only required a quick demonstration, as the objective of the game was simple to understand. The game was performed independently by the DLs on their personal iPads (Generation 9, with a 10.2" screen).

The duration of the activities was kept to around 12 minutes to avoid a decrease in performance over time, due to motivational decrement (lack of motivation due to boredom) (Helambang, Taatgen, and Cnossen, 2019), habituation (decrease in response due to the same task being repeated) (Manly et al., 1999), or resource depletion (attention being used up due to the difficulty of the task) (Thomson, Besner, and Smilek, 2015).

3.6.2 The Number Cards Activity

The Number Cards Activity (Figure 6) is a QToD-led activity accessed using the website www.toytheatre.com/number-cards/. The idea for this format was inspired by research showing that playing card games can improve working memory (Benzing et al., 2019). This activity targets the PL by encouraging the use of rehearsal strategies. Unlike the other activities, this one is more flexible, and adaptable for different abilities by the QToD. Even though the digit version was used, this version can be easily converted into a physical version using real playing cards.

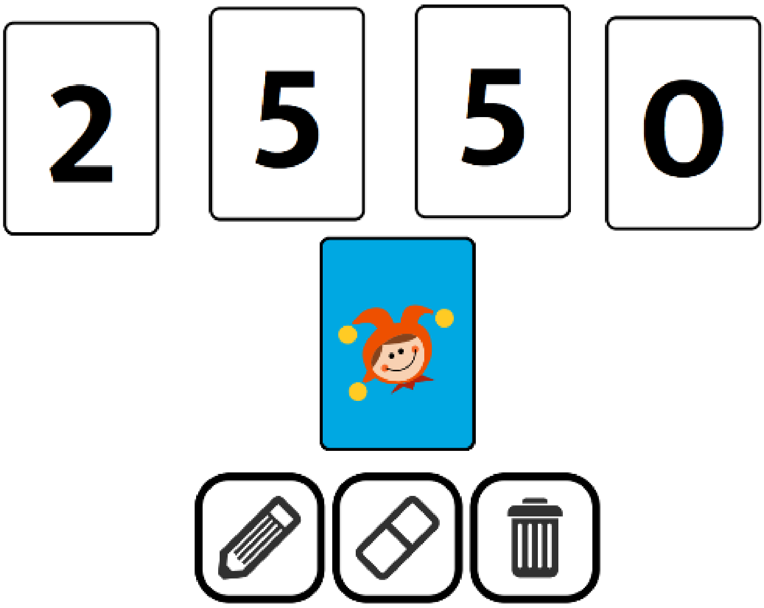

Figure 6. *Number Cards Activity. Screenshot from www.toytheatre.com*

There were different activities administered. In the basic activity, cards numbered 1 to 9 were dealt, and the DLs were asked to memorise them. The cards were then turned over (hiding the numbers), and mixed. Some of the cards were then unturned, to reveal their numbers. The goal was for the DLs to identify the hidden numbers on the turned-over cards. The activity was adjusted depending on the ability of the DLs, by varying the number of cards dealt and turned over to be recalled. This activity was designed to encourage DLs to use rehearsal strategies to recall number sequences. One strategy involved the memorisation of a sequence of cards using a rehearsal strategy. When some of the cards were turned over, they could use the rehearsed sequence to spot the 'missing' number. An extension to this activity involved turning over *all* the cards! In some classes, DLs with weaker WM skills worked with a teaching assistant for support.

Another activity involved recalling the numbers in ascending or descending order. This task involved using rehearsal strategies, and the CE in deciding which strategies to use. An example taught encouraged them to combine information from the Long-Term Memory (LTM) and STM (in a component called the episodic buffer) and use the CE to compare and solve problems. For example, if they were required to recall a sequence like 1, 2, 4, 5, 6, 8, 9, they could use prior learned information from the LTM (the sequence 1, 2, 3, 4, 5, 6, 7, 8, 9) and recognise it is the same as the new sequence, but with the numbers 3 and 7 missing. In this way, the DLs would reduce the cognitive load by engaging the LTM and CE to help them solve problems.

3.6.3 The Picture Matching Pair Game

The third activity in the intervention programme is called the Picture Matching Pair game. This is a QToD-led activity but can be performed independently by the DLs. In this activity, DLs are required to find matching pairs in a grid of unturned picture cards. They need to turn over two cards at a time, attempting to find a matching pair. If the cards matched, they then disappear from the grid. If they do not match, both cards are turned over and the DLs are required to select two more cards. This process continues until all pairs have been found. The cards feature pictures of various common objects, such as a house, dog, and balloon.

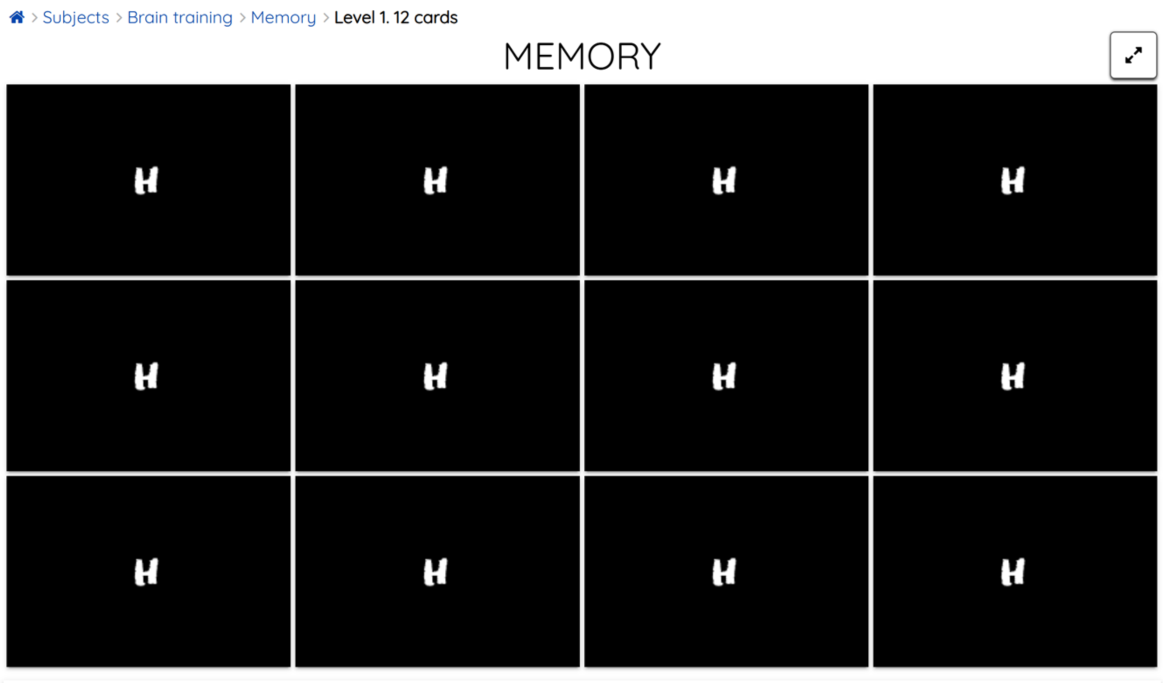

Figure 7. *Picture Matching Pair Game. Screenshot from www.helpfulgames.com*

In this study, the version of the Picture Matching Pair Game (Figure 7) was accessed through the website https://www.helpfulgames.com/subjects/brain-training/memory.html. There are many difficulty levels, and the QToD considered 12 and 16 pairs the most appropriate challenge level. This game was chosen for the intervention firstly, because it was a 'fun' activity that was likely to keep the DLs engaged and focused. Additionally, research has shown that playing card and board games can lead to enhancements and improvements in the WM of learners (Estrada-Plana et al., 2019), including the Picture Matching Pair game (Sivakumar, 2022).

Two versions of the activity were played. The independent version encouraged the DLs to remember each picture card by memorising their positions. The second version was a QToD-led activity. This involved creating a narrative involving the picture cards and linking them together in a story manner. By remembering the narrative, they were then able to use it to recall the positions of the cards. The DLs started by memorising the card in the top left-hand corner first, moving one card to the right, until the end of the top row was reached. This process was repeated using the second row and continued until the bottom right-hand card was reached. Even though the activity was led by the QToDs, the DLs contributed their ideas to the narrative. This was very important, as involving the DLs in creating strategies for recall is more effective than passive learning (Oaks, 1995; Roediger, 1980). While the first activity engaged largely the VSSP, the second activity required the DLs to engage other areas of their WM including the CE, by organising and sequencing the picture cards.

3.7 Statistical Considerations

At the end of the intervention programme, the post-tests were administered under the same conditions, and the results were recorded. The statistical program SPSS Statistics 29.0.1.0 was used to generate and analyse the data collected. This software was chosen because of its reliability. This was supported by a review by Masuadi et al. (2021) of 10596 articles from the research publisher PubMed, which found that SPSS was the most used statistical software, appearing in over 52% of their articles.

3.7.1 Tests for Normality

Before applying any statistical technique to analyse the data, it was important to determine if the data are normally distributed. This is because normally distributed data allow for the use of parametric tests like the paired *t*-test. These tests are more precise and powerful than non-parametric tests, which do not require normally distributed data, and are more sensitive at detecting differences, when they exist (Politi, Ferreira, and Patino, 2021).

Before conducting a normality test, we need to check that the sample size is large enough. Allen, Bennett, and Heritage (2014) and Dodge (2008) suggest a sample size of at least 30 is necessary. However, Julious (2005) recommends a minimum of 24 participants for meaningful calculations, while Sim and Lewis (2012) suggest a larger sample size of 50. Using these estimates, Hooper (2019) suggests that a sample size between 24 and 50 can be justified. In the current study, the sample size is 33, which falls within the recommended range, allowing for the data to undergo normality checks.

SPSS uses the Shapiro-Wilk test (Shapiro and Wilk, 1965) and the Kolmogorov-Smirnov test (Chakravarti, Laha, and Roy, 1967) to check for normality. The Shapiro-Wilk test is generally used for smaller sample sizes ($N < 50$), while the Kolmogorov-Smirnov test is typically used for larger sample sizes ($N \geq 50$) (Mishra et al., 2019). Given that the sample size in the current study is 33, the Shapiro-Wilk test was chosen. It is important to note that these tests are not always accurate. When the Shapiro-Wilk test does not show normality, it is important to have a second opinion, by using graphical and numerical methods. In such cases, the histograms will be checked against the standard bell curve, and QQ plots checked against a straight line. The skewness and kurtosis values will be examined to check their fit against a normal distribution. However, interpreting these aspects requires expertise and careful judgment, as a statistically competent practitioner is needed to accurately assess the data’s normality (Mishra et al., 2019).

For a distribution to be normal, the values of skewness and kurtosis must be within predefined boundaries. Skewness values between –1 to +1 are considered excellent (Hair et al., 2022), while values that lie between –2 and +2 are satisfactory (Byrne, 2010, Hair et al., 2010). Similarly for kurtosis, values between –2 to +2 are adequate, but values outside this range suggests that the distribution may be too peaked or too flat (Hair et al., 2022) for a normal distribution. If the data fail the normality tests, alternative methods will be needed to compare pre- and post-test data.

In the current study, the Shapiro-Wilk test was used to check for normality. For one of the tests however, additional graphical and numerical methods were needed. The QToD was qualified and competent in analysing both the graphical and numerical data to ensure the accuracy of the normality checks.

3.7.2 *t*-Tests, Significance, and Effect Sizes

Once the normality tests were completed, the paired *t*-test was used to compare the pre- and post-test data, as both groups were related (Bland, 2015). One of the aims of the *t*-test is to see if there is a significant difference between the pre- and post-test data by generating a *p*-value. The other is to measure the magnitude of the difference via an effect size. This value is equally, if not more, important than showing if a significant difference exists. Cohen (1990) himself emphasized that "*the primary product of a research inquiry is one or more measures of effect size, not P values*" (p. 1310). In other words, knowing whether there is a significant difference in results is important, but understanding the magnitude of that difference is crucial (Sullivan and Feinn, 2012)

There are several methods to measure the effect sizes, including Cohen's *d* (Cohen, 1969), Glass's Δ (Glass, 1976), and Hedges *G* (Hedges, 1981). These methods have different applications. For example, Cohen's *d* and Hedges' *G* are very similar as they both use a weighted average to calculate their standard deviation. However, Hedges' *G* (Hedges and Olkin, 1985) includes a correction factor for small sample sizes ($N <$ 20), which makes it ideal for smaller groups. When $N \geq 20$, Cohen's *d* and Hedges' *G* yield very similar effect sizes, so Cohen's *d* is often used. When there is a large variance in the standard deviation between pre- and post-tests, Glass's Δ may be a more suitable measure.

Cohen (1988, 1998) proposed that a value of $d = 0.2$ represents a small effect, $d = 0.5$ a medium effect, and $d = 0.8$ a large effect. These criteria were not rigorous in their derivation and Cohen himself said they were "*no more reliable a basis than my own intuition*" (Cohen, 1988, p. 532). He added that they should be used as a guide when no empirical data are available, and it is always better to explain the effect sizes of data from the same area of research. Research into different effect sizes across different disciplines (Hemphill, 2003), and within disciplines such as psychology (Schäfer and Schwarz, 2019), have revealed different criteria that match small, medium, and large effect sizes. Morris and Fritz (2013) reviewed many studies in memory research, and by calculating the medians and the quartiles of those studies, found values of d = 0.25, 0.57, and 0.99 for small, medium, and large effect sizes. These were similar to the guidelines by Cohen (1988), except for the large effect size which was much higher. In this study, the values of Morris and Fritz (2013) will be used as the criteria, since they are found by using clinical data.

In our study, SPSS was used to calculate the effect size, which was calculated with the data from the paired *t*-test analysis. This provided additional insight into the magnitude of the impact of the intervention.

3.8 Ethics

Ethical approval for the study protocol was granted by the University of Hertfordshire (appendix i).

Before the start of the assessments and the intervention programme, the D/deaf learners were informed about the study. The aims and objectives were explained to them (appendix iii, iv). Written consent was obtained from learners aged 18 or older (appendix vi), and from the parents or carers of learners under 18 years of age (appendix ii, v), for the use of their results and observations during the intervention. Written assent was also obtained from learners under 18 years of age (appendix vii, viii). Due to the risk of contamination through sharing equipment and being inside an enclosed space, the room used was regularly ventilated and equipment was disinfected following each use.

4. Results Analysis

4.1 General Observations and Exploratory Analysis

Forty D/deaf learners were approached; six were excluded, as one did not return the consent form, and five families of DLs did not provide consent. Of the remaining 34 DLs, one participated in less than 80% of the required time, so their test scores were not included in the results analysis. The final sample consisted of 33 DLs, aged 12–18 (18 male, 15 female), with moderate to profound hearing loss (2 moderate, 8 severe, 23 profound). The attrition rate was 2.9%.

Pre-test data were collected over the period of one-week before the start of the intervention programme. Similarly, the post-test data were also collected over a one-week period after the end of the intervention programme. The mean age of the DLs on the first day of pre-test was 15.9 years (*M* = 15 years and 8 months, *SD* = 2 years 0 months). The youngest learner was aged 12.3 years (12 years and 4 months), and the oldest was aged 18.7 years (18 years and 8 months).

A comparison of the pre- and post-test results can be seen in Table 1 and Table 2.

Table 1. *Pre-test scores*

Assessment	Minimum score	Maximum score	Mean score
FDSp pre-test	2	8	5.39
BDSp pre-test	1	13	7.21
CBTT pre-test	1	10	6.52

Table 2. *Post-test scores*

Assessment	Minimum score	Maximum score	Mean score
FDSp post-test	3	9	5.73
BDSp post-test	2	13	8.30
CBTT post-test	3	11	7.36

In the FDSp, the mean post-test score was higher than the mean pre-test score (M = 5.73 compared to M = 5.39). In the BDSp, the mean post-test score also exceeded the mean pre-test score (M = 8.30 compared to M = 7.21). For the CBTT, the mean post-test score was also higher than the mean pre-test score (M = 7.36 compared to M = 6.52). These results suggest an overall improvement across all tests after the intervention.

4.2 Normality Tests

The difference between the pre- and post-test scores was calculated, and a test for normality was performed on these values, with the results displayed in Table 3. Additional descriptive data generated are presented in Table 4. The Kolmogorov-Smirnov results generated by SPSS (which were not included in the tables) were disregarded because the test is not considered reliable with small sample sizes (N = 33). This value falls below the recommended threshold of N = 50, so only the results from the Shapiro-Wilk test were used to assess normality.

Table 3. *Results of the Shapiro-Wilk test performed on the difference in the pre-post scores*

Assessment	Shapiro-Wilk (W value)	Significance
FDSp difference	0.929	0.034
BDSp difference	0.956	0.202
CBTT difference	0.944	0.087

Table 4. *Descriptive data for the difference in the pre-post scores*

Assessment	Mean	Skewness	Kurtosis
FDSp difference	0.33	0.223	0.144
BDSp difference	1.09	0.475	0.180
CBTT difference	0.85	0.041	0.852

The results showed that, for the CBTT difference, $W(33) = 0.944$, $p = 0.087$. Since $p > 0.05$, there was no significant deviation from normality, indicating that the data were normally distributed. Similarly, for the BDSp difference, $W(33) = 0.956$, $p = 0.202$. Since $p > 0.05$, the results indicated no significant deviation from normality, suggesting that the data were normally distributed. However, for the FDSp difference, $W(33) = 0.929$, $p = 0.034$. The results revealed a significant deviation from normality as $p < 0.05$, indicating that the data significantly deviated from a normal distribution.

As outlined in section 3.7.1, a rejection of normality by the Shapiro-Wilk test does not always mean that the distribution is non-normal. Based on the analysis of the FDSp difference, descriptive statistics were used to further assess normality. The skewness was found to be 0.223, which suggests the distribution is relatively symmetrical. The kurtosis value of 0.144 indicates that the distribution has tails like a normal distribution. Graphical evidence from Figure 8 (the QQ plot) and Figure 9 (the histogram) provides further evidence that the data are normally distributed, as the QQ plot approximately follows a straight line, and the histogram approximately follows the bell-shaped curve. Considering this strong evidence from both numerical and graphical methods, we can confidently assume that the FDSp difference is indeed normally distributed.

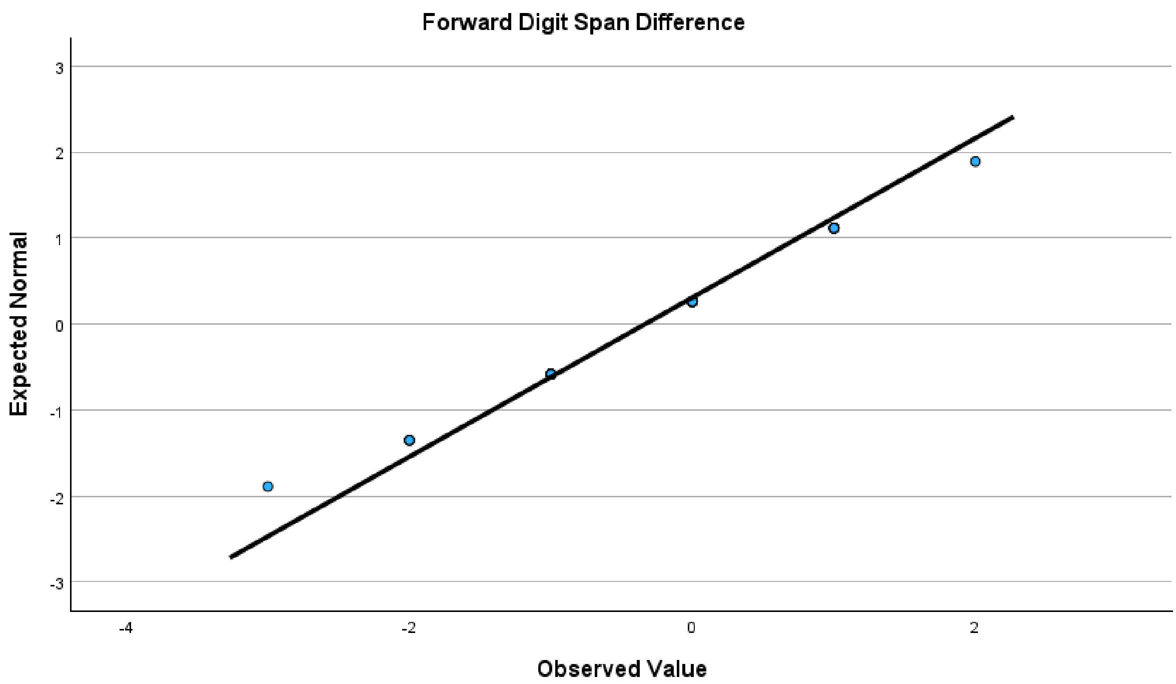

Figure 8. *QQ plot showing the FDSp difference*

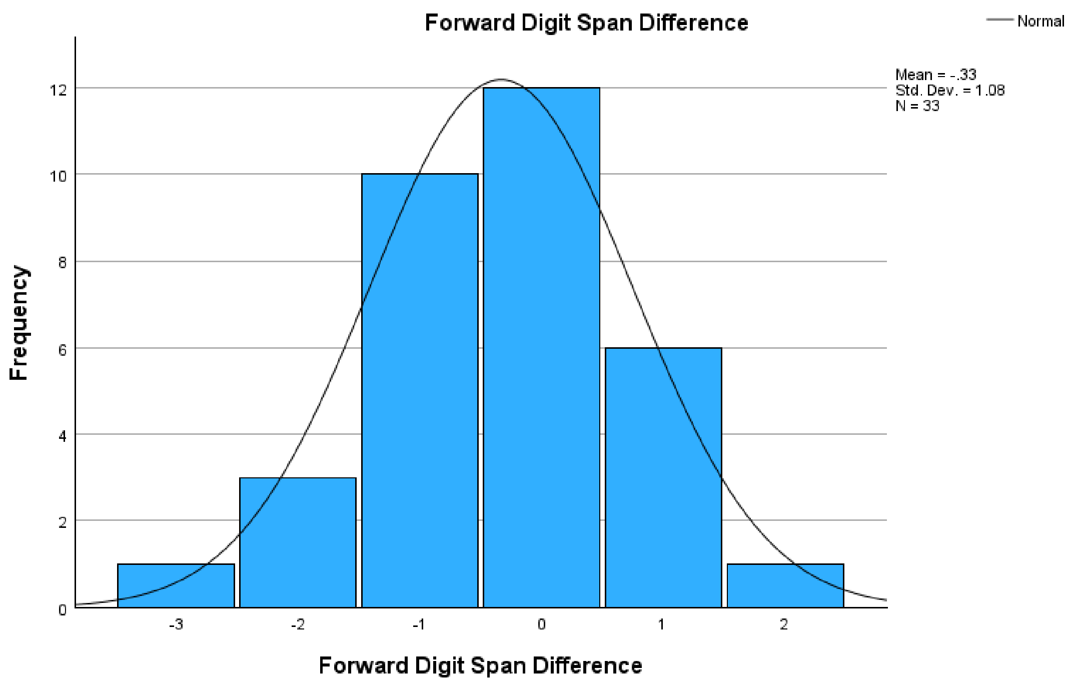

Figure 9. *Histogram showing the FDSp difference distribution*

4.3 *t*-Tests, Significance, and Effect Size

Having established that the difference distributions for the FDSp, BDSp, and CBTT all follow a normal distribution, paired *t*-tests were conducted to determine whether the post-test results showed a significant difference compared to the pre-test scores.

Table 5. *Paired t-test results comparing the pre- and post-tests*

Test	Mean	Standard deviation	*t*-Value	Degrees of freedom	Significance	Effect size
FDSp	0.333	1.080	1.773	32	0.043	0.309
BDSp	1.091	2.542	2.466	32	0.010	0.429
CBTT	0.848	1.460	3.338	32	0.001	0.581

Tables 1, 2, and 5 show that, when comparing the pre-test and post-test scores for the BDSp, the results indicate a significant increase in scores from the pre-test (M = 7.21, SD = 2.891) to post-test (M = 8.30, SD = 2.158). The results of the *t*-test showed that $t(32) = 2.466$, $p = 0.010$. Since $p < 0.05$, this suggests that learners' performance improved significantly after the intervention. With Cohen's *d* = 0.429, the effect size suggests that this improvement is small.

When comparing the pre-test and post-test scores for the CBTT, the results also indicate a significant increase in scores from the pre-test ($M = 6.52$, $SD = 2.476$) to post-test ($M = 7.36$, $SD = 2.148$). The *t*-test showed that $t(32) = 3.338$, $p = 0.001$. Since $p < 0.05$, this suggests that the learners' performance improved significantly after the intervention. With Cohen's $d = 0.581$, the effect size suggests this improvement is medium.

For the FDSp, the results also indicated a significant improvement from the pre-test ($M = 5.39$, $SD = 1.619$) to post-test ($M = 5.73$, $SD = 1.645$). The results of the *t*-test showed that $t(32) = 1.773$, $p = 0.043$. Since $p < 0.05$, this suggests that the learners' performance improved significantly after the intervention. However, Cohen's $d = 0.309$, suggesting that the effect size is small.

5. Discussion

5.1 The Hypothesis

The aim of the current study was to evaluate the impact of the intervention on the WM of DLs as a way of supporting their mathematical learning. It was hypothesised that the intervention would lead to an improvement in WM performance. The results of the statistical analysis in the previous section show significant improvements in all three assessments, leading to the rejection of all three null hypotheses. Therefore, there is evidence to support the alternative hypotheses which state that there are significant *increases* in the mean WM scores from pre-test to post-test of DLs between the ages of 12 and 18 who completed the intervention programme.

5.2 Forward and Backward Digit Span Comparisons

The previous section revealed that there were significant improvements in WM performance in all three tests. We also saw small effect sizes for the BDSp and the FDSp, and a medium effect size for the CBTT. However, the effect sizes raise some interesting questions. The effect size of the FDSp (Cohen's $d = 0.309$) is the smallest of the three tests, smaller even than the BDSp (Cohen's d = 0.429). This is surprising, as the BDSp is often recognised as being more challenging than the FDSp due to the engagement of the CE. This is evidenced in the literature review on a range of HLs by Donolato, Giofre, and Mammarella (2017), who found that, in general, learners scored lower on their assessments of the BDSp than on the FDSp. The question could be reframed as, did the DLs in the current study perform more poorly on the FDSp? Or did they perform better on the BDSp? Both possibilities are plausible.

Older research from the 1990s can provide possible explanations for the low effect size in the FDSp as this test relies heavily on the rehearsal process, which is less frequently used by DLs (Bebko and Metcalfe-Haggert, 1997). During the current intervention, there were numerous occasions when the DLs could practise their rehearsal strategies. From observations, it was clear that not all DLs fully adopted or developed this strategy. DLs who were not able to, or did not feel comfortable using a verbal rehearsal process were encouraged to use a sign language-based rehearsal technique, as there are suggestions that it may be possible to develop a ‘visuospatial’ phonological loop (Wilson and Emmorey, 1997). While some DLs used this technique, many struggled or simply did not engage with it. When asked who used the rehearsal strategy, some DLs responded that they did use it vocally, while others preferred to use subvocal rehearsing. Others mentioned they did not feel comfortable using sign language to rehearse as well. Several DLs mentioned different reasons for this, from “*I don’t need it*,” “*I’m too shy*,” to “*I don’t want to distract the other learners.*” These barriers suggest that the rehearsal strategy was not fully embraced by all DLs, which may have impacted the effectiveness of the intervention. To address these concerns in future studies, it may be better to conduct the intervention in smaller groups, or on an individual basis. This could provide a more supportive and comfortable environment where DLs feel more at ease discussing and adopting strategies without the concerns of disrupting others. Not surprisingly, DLs who embraced the use of rehearsal strategies in the classroom, also used them in their post-tests.

In general, DLs accessed information from the QToD in many ways. Some would make direct eye contact and use their hearing to access the information. Others preferred different strategies such as listening, speechreading, and observing the signing hand through their peripheral vision. A few looked at the hands only, without referencing the assessor’s face. Some of these strategies that were used, were confirmed through questioning at the end of some of their tests. There is no current research looking into such rehearsal strategies, so it could be incorporated in future studies.

To help explain why the DLs in the current study achieved a larger effect size in the BDSp than the FDSp, we need to look at strategies that could be used. Even though research points to the CE as the area that helps the recall of the BDSp, research has shown that verbal information can be supported by using a visuospatial process (Darling et al., 2012; De La Iglesia, Buceta, and Campos, 2005; St Clair-Thompson and Allen, 2013). This has been investigated further using neuroimaging (Hoshi et al., 2000). Since DLs have heightened visual awareness, it may not be surprising that they may employ visuospatial techniques to support their reorganising of the digits within the assessment. In fact, during observations made in both pre- and post-tests, differences were seen in how the DLs interacted with the QToD. A larger number of DLs seemed to focus intently on the hand patterns being signed. This was very clear as many would focus their gaze down to see clearer hand patterns. Some DLs were also observed 'staring into space' more frequently during the BDSp test than the FDSp, which may suggest that they were using different parts of their WM, such as the visual memory to help them retain information in the BDSp task (Darling et al., 2012; De La Iglesia, Buceta, and Campos, 2005; St Clair-Thompson and Allen, 2013).

Since the assessment sessions were not recorded, it was not possible to conduct a detailed analysis of each DL's body language and non-verbal cues. This has limited the ability to perform a deeper analysis. However, these observations may provide opportunities for future research into the strategies that DLs may use when completing the FDSp and BDSp tasks. This could allow further investigations into how DLs engage with memory tasks, particularly in terms of the different strategies they use for visual and verbal memory tasks.

5.3 Digit Span Structure – A Critical Look

Two of the tests used in this study were from the WISC-V (Wechsler, 2014). The Working Memory Index of the WISC-V includes core subtests 'Digit Span' and 'Picture Span'. Within the Digit Span subtest, learners are required to complete three tasks: the FDSp, BDSp, and a sequencing span task.

In the current study, only two of the tasks within the Digit Span subtest were administered: the FDSp and BDSp. The reason was to help maintain attention, as performing all the tasks would have been too challenging for the average DL, leading to unreliable results. However, it is important to recognise that the WISC-V test was not designed to be modified, so selecting parts from the Working Memory Index's many components does not give a comprehensive picture of the DLs' WM.

While some assessors must reduce the number of assessments to ensure accessibility for their learners, some researchers argue that the tests are not detailed enough. Conway et al. (2005) in their analysis of the Digit Span subtest in the WAIS test (Wechsler, 1997) (which is structurally similar to the WISC-V), argue that having only two sequencing items in each round is insufficient for a true test of WM capacity. They suggest that the two-questions-per-round be replaced by four or five items. Additionally, to advance to the next round, learners should achieve an accuracy score of 67 – 80%. While this approach may yield more accurate results due to the increased number of questions, it will make the test longer, and less accessible for some learners. While acknowledging that tests with two-questions-per-round may not provide the most comprehensive view about the DLs' WM, it does allow us to gather data that we otherwise may not be able to obtain. In further studies, limitations of selectively using components will need to be considered, within the practicalities of working with specific cohorts and their needs.

5.4 Corsi Block Tapping Test (Qualitative Information)

The CBTT showed the largest effect size (Cohen's *d* = 0.581) suggesting a meaningful improvement in DLs' visuospatial memory. This outcome is not surprising, as DLs typically have heightened spatial awareness, which may have contributed to their strong performance.

Even though many DLs could recall the locations of the flashing lights, they often struggled to recall the order in which they appeared. This suggested, while their visuospatial memory was working well, their ability to process sequencing, a task handled by the CE was less efficient. This observation was consistent with research by Zarfaty, Nunes, and Bryant (2004), involving young learners and McFayden et al. (2023) involving adult learners, which found that simultaneous presentation of stimuli helped reduce cognitive load, particularly in tasks that involve sequencing.

A key consideration for QToDs when teaching mathematics to DLs is to present information using clear, visual diagrams rather than relying on sequential presentation, unless the sequential aspect is important to the task. This can help minimise cognitive load and allow DLs to focus on visualising mathematical concepts.

5.5 A Comparison with Nunes et al., (2012)

The idea for the current intervention was motivated by the study by Nunes et al. (2012); however, there are notable differences. The current study focused on mathematical elements, and did not involve linguistic tasks, unlike the study by Nunes et al. (2012). The results from the current study revealed effect sizes between d = 0.309 and d = 0.581, which in comparison with Nunes et al. (2012), where d = 0.78, were smaller. Reasons for this difference could be explained by many differences in methodologies.

Nunes et al. (2012) involved a sample of 150 deaf children aged 5-11 years (*M* = 8 years 5 months, *SD* = 1 year 6 months), whereas our study focused on 33 DLs aged 12-18 years (*M* = 15 years 8 months, *SD* = 2 years 0 months). The composition of the two groups was vastly different in terms of the degree of deafness. In our study, 70% of the DLs were profoundly deaf, whereas in Nunes et al. (2012), the figure was 40% (see Table 6).

Learners with profound deafness are more susceptible to language deprivation, which can have a larger impact on their EF (Hall et al., 2016). This could result in greater difficulties with cognitive tasks like the BDSp, which assesses the CE component of WM. It is important to note, however, that DLs raised using BSL are an exception, as they generally do not show weakened EF (Boutla et al., 2004). Therefore, differences in the impact of the intervention could also be a result of varying levels of language exposure and support among DLs in the two studies. It is important to note that in the current study, there was only one native DL raised using BSL, and therefore this should not affect the conclusions regarding the effect size of both studies.

Table 6. *Learners in the current study and Nunes et al. (2012) with deafness level percentages. The current study uses BATOD descriptors for levels of deafness*

Severity of deafness	Nunes et al. (2012)	Current study
Moderate	22 (15%)	2 (6%)
Moderate/severe	17 (11%)	N/A
Severe	34 (23%)	8 (24%)
Severe/profound	17 (11%)	N/A
Profound	60 (40%)	23 (70%)
Total	150 (100%)	33 (100%)

Table 7. *Learners in the current study and Nunes et al. (2012) with amplification technology percentages*

Type of aided hearing	Nunes et al. (2012)	Current study
Cochlear implants	48 (32%)	18 (55%)
Hearing aids	102 (68%)	9 (27%)
Cochlear implants & hearing aids	0	1 (3%)
No equipment	0	5 (15%)
Total	150 (100%)	33 (100%)

In Table 7, the percentage of cochlear implant users is higher in our study than in Nunes et al. (2012). This may be explained by the fact that profoundly DLs generally benefit more from cochlear implants than from hearing aids (Bittencourt et al., 2012; Boerrigter et al., 2023), which could play a role in enhancing auditory input and improving WM cognitive functions.

Another reason that may explain the difference in effect sizes is that Nunes et al. (2012) excluded DLs with additional needs from their study. The current study included learners with and without additional needs, provided they met the eligibility criteria: the ability to understand the tasks given, and attendance of at least 80%. The National Deaf Children's Society (NDCS, 2025) suggests that between 30-40% of young DLs have additional need, implying that a significant portion of the DLs in the current study likely had additional needs. This could influence their cognitive functioning and response to the intervention.

Research on HLs has shown that those with additional needs tend to have weaker performance on WM tasks, particularly in the VSSP, CE, and verbal WM (PL) (Alloway et al., 2005; Hasselhorn, 2007; Van der Molen et al., 2007). Given the limited research on WM in DLs, it is reasonable to hypothesise that DLs with additional needs may experience even greater challenges with their WM. This area requires further investigation to help us better understand how additional needs affect WM performance in DLs and to improve future targeted interventions.

5.6 Other Intervention Programmes

The study by Nunes et al. (2012) and our current study, demonstrate that it is possible to improve WM within a school-based setting. However, what about programmes that can be implemented at home? The computer activities used in the current study, the Simon Game and the Picture Matching Pair Game can be used by DLs at home independently, even after the study has finished, allowing them to continue their WM training. With guidance from the QToD and with parents' and carers' involvement, many activities used in the intervention programme can be continued at home.

There are also more formal alternative programmes available to support DLs. Kronenberger et al. (2011) conducted an intervention programme using the Cogmed Working Memory Training Programme (Cogmed, 2025; Klingberg et al., 2005). The programme was designed to allow DLs to work independently, while the difficulty level adjusts automatically to provide appropriate challenge. This was conducted over a five-week period at home involving nine DLs aged between 7 to 15 years. At the end of the programme, there were noticeable improvements in both verbal and visual memory, suggesting that independent, home-based interventions can be effective in enhancing WM.

In subsequent follow-up assessments, Kronenberger et al. (2011) found that performance decreased after one month. After six months, the performance was even lower than after the first month. This suggests that with this home-based intervention, it is difficult to maintain the improved performance once the initial intervention has finished, unless there is ongoing reinforcement.

The debate regarding Cogmed and its effectiveness is still ongoing. Studies involving HLs, including those with ADHD, support the efficacy of Cogmed (Bharadwaj, Yeatts, and Headley, 2022; Roche and Johnson, 2014). The meta-analysis by Bharadwaj, Yeatts, and Headley (2022) which reviewed ten published studies found that improvements can be achieved in both the short and long term. However, other studies have shown limited or no impact (Deniz Aksayli, Sala, and Gobet, 2019; Hulme and Melby-Lervåg, 2012; Yanwen, 2020).

Based on these interventions, it is clear that WM should be targeted on multiple levels for improvements to be sustained. This will include practices within and outside of the classroom involving events and activities which are part of the DLs' daily routine.

6. Further Research and Conclusion

6.1 Limitations and Future Considerations

Even though the current study was effective in showing that an intervention programme can support improvements in WM, this study does have its limitations.

The current study involved a sample of 33 DLs. By **recruiting a larger and more diverse sample** that better represents the broader D/deaf population, the data generated would give a more representative and generalised understanding of the effectiveness of the intervention.

If a larger group could be recruited, a **randomised control trial** could be implemented. This method is very reliable and is considered the gold standard (Hariton and Locascio, 2018) and would enhance internal and external validity by reducing bias compared to other designs. It makes correlations clearer and subsequent data could be generalisable to larger populations leading to more reliable and impactful findings. However, it would be difficult to recruit such numbers for the trial, requiring more organisation between different schools and colleges, and is often expensive and time consuming to run (Hariton and Locascio, 2018) but ultimately, would be a worthwhile investment.

Extending the intervention programme would be another way of improving the study. It was clear that many DLs were not comfortable using the rehearsal strategies. A longer intervention programme conducted with smaller groups would have allowed for more practising time and support from the QToD and classroom assistants. However, a longer intervention programme could lead to boredom with the activities resulting in decreased motivation and engagement. Nevertheless, with careful planning and the addition of different activities, this extension could help maintain interest over a longer period. Involving parents and carers to practice these tasks at home could provide a more holistic approach for the DLs' learning.

This study can be extended by further **investigating the sustainability of the intervention**, by repeating post assessments at the 6-month and 12-month points, as highlighted by Kronenberger et al. (2011), WM skills often start to decline soon after the intervention stops. Another idea would be the involvement of additional ‘booster' activities to see if they can help maintain the level of enhanced WM. Alternatively, there could be a permanent integration of a WM programme into the mathematics lessons, but in a reduced capacity.

In the current study, the pre- and post-tests were conducted by *one* QToD. This meant that the delivery was consistent for all DLs, reducing biases that could otherwise affect the WM scores. The intervention programme was less consistent, as the activities were delivered by *two* QToDs, each having their own teaching style, methods, and experience. Even though regular meetings between the QToDs were held and feedback on DLs' performance and interaction was discussed, **a standard operating procedure** could be used to minimise the differences in future intervention programmes.

The current assessments were selected, because they gave a broad overview of the WM components, however, not enough to give a deeper insight. Adding **more targeted tests of EF** could generate more useful data; however, it may over-assess, frustrate, and demotivate the DLs leading to unreliable results. While it is possible to conduct the extra tests with more resilient DLs, this would likely lead to smaller sample sizes, ironically making the results less reliable.

Similarly, for the **intervention programme, increasing the number of tasks** could target many more areas of the WM. It could also help the DLs maintain interest due to a larger variety of tasks and additionally help to reduce the practice effect (Shipstead, Redick, and Engle, 2012) which could inflate results caused by practicing the same limited tasks. However, adding more tasks would require additional time for the QToD to prepare resources, train to use the tasks, and conduct the assessments.

Implementation of **a mixed methods approach** could give a better overview of the intervention study. While the current study incorporates observations and feedback from DLs that can help understand them more, it does not investigate in depth, the DLs' perspectives. Adding a **qualitative element**, through interviews about their enjoyment, difficulties, and motivation in the activities, can be used for future planning and improvement. It might even tell us more about the strategies they used. The DLs' responses can be cross referenced back with their test data, to give a fuller picture of their results.

6.2 Consideration of Access to the Intervention

When the intervention programme was introduced to the DLs, it was important that the study was explained in full. They needed to know that it was their choice to be involved and the benefits that they might gain, and that they were not participating due to pressure and influence out of respect for the authority figure (the QToD) (Gallagher et al., 2010; Nyambedha, 2008). In the current study, forty families were approached for the study; six families declined to give consent, and one family, despite repeated contacts, did not respond. A variety of reasons were given by the families for not wanting to give consent. In research, there are many reasons why families may not give consent. Taplin et al., (2021) and Powell et al., (2020) suggest that parents or carers can be hesitant about their child's involvement in research, especially if their child is considered vulnerable. Creating opportunities to meet families during parents' evenings and other events would allow QToDs to provide more information and address any concerns about the study. It can also help to build better relationships (Bogolub and Thomas, 2005) which can help reduce the hesitancy in providing consent for their child. Furthermore, it could explore potential barriers these families might have in accessing such interventions. In our study, this was difficult, as the intervention programme began early in the academic year and there were no relevant opportunities to meet with parents due to time constraints.

6.3 Conclusion

While there have been many intervention programmes involving HLs and WM (EEF, 2024; Rowe et al, 2019), very few have involved DLs. Nunes et al., (2012) conducted an intervention programme that involved young learners between the ages of 5 and 11. However, there has been limited research concerning older DLs between the ages of 12 and 18. This study aims to contribute to this area of research. The current study has shown that for DLs in the age range of 12 to 18, it is possible to improve their WM using an intervention programme involving a mixture of independent and QToD-led activities. This is important, as improved WM can support those DLs further in their cognitive development.

A deeper understanding of mathematics is a key benefit of improved WM. This can significantly impact DLs' learning, leading to better problem-solving skills, improved understanding, and potentially better qualifications, so that they can develop a more independent and fulfilling life. Since mathematics is a foundational skill needed to live independent lives, strengthening DLs' ability to recall, retain and manipulate information in the WM can help in achieving this.

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Appendices

i. Ethics Letter of Aproval

To: Cecil Lee

Your application for ethics approval for the study listed below has been **conditionally** approved by the Social Sciences, Arts and Humanities Ethics Committee with Delegated Authority. **Please read this letter carefully.**

Study Title: A feasibility study in an intervention program to support deaf children in improving their working memory

Your UH protocol number is: **0517 2025 Jan SSAH**
This reference must be quoted on all paperwork, including advertisements for participants.

If you wish to use the UH Ethics Committee logo disclaimer in your communications with participants, please find it in our UH Ethics Canvas site under 'Units - Application Forms': UH Ethics Approval (instructure.com.

This ethics approval expires on 31/03/2025

Conditions of approval specific to your study:

Ethics approval has been granted subject to the following condition being seen and approved by the supervisor as addressed prior to recruitment and data collection:

- Parent or carer permissions must be obtained for all students below the age of 18.

Amending your protocol

Individual protocols will normally be approved for the limited period of time noted above. Application for minor amendments (including time extensions) of a protocol, may be made for a maximum of 4 working weeks after the end date of that protocol.

It is expected that any amendments proposed via the online system will be minor. Should substantial modification be required, it would be necessary to make a fresh application for ethical approval.

Note that you must obtain approval from the relevant UH Ethics Committee with Delegated Authority **prior to implementing any changes**. Failure to do so constitutes a breach of ethics regulations (UPR RE01).

Adverse circumstances
Any adverse circumstances that may arise because of your study/activity must be reported to ethicsadmin@herts.ac.uk as soon as possible.

Permissions
Any necessary permissions for the use of premises/location and accessing participants for your study/activity must be obtained in writing prior to any data collection commencing. Failure to obtain adequate permissions may be considered a breach of this protocol.

Ethics Administration Team

ethicsadmin@herts.ac.uk

ii. Participant Information Sheet (Parents and Carers)

UNIVERSITY OF HERTFORDSHIRE

ETHICS COMMITTEE FOR STUDIES INVOLVING THE USE OF HUMAN PARTICIPANTS ('ETHICS COMMITTEE')

PARTICIPANT INFORMATION SHEET (PARENTS)

1 Title of study

A feasibility study in an intervention programme to support deaf learners in improving their working memory

2 Introduction

Your child is being invited to take part in a Master's study. Before you decide whether to allow them to do so, it is important that you understand the study that is being undertaken and what your involvement will include. Please take the time to read the following information carefully and discuss it with others if you wish. Do not hesitate to ask us anything that is not clear or for any further information you would like to help you make your decision. Please do take your time to decide whether or not you wish to take part. The University's regulation, UPR RE01, 'Studies Involving the Use of Human Participants' can be accessed via this link:

https://www.herts.ac.uk/about-us/governance/university-policies-and-regulations-uprs/uprs
(after accessing this website, scroll down to Letter S where you will find the regulation)

Thank you for reading this.

3 What is the purpose of this study?

Previous studies have suggested that deaf learners might experience difficulties with their working memory. Since working memory is important in storing short term memories and manipulating information, weaker working memory can impact the their ability to learn mathematics. The purpose of this study is to find out how effective an intervention programme is, in supporting deaf learners to improve their working memory. In the programme, deaf learners will have the opportunity to practice and train their working memory through interactive games and teacher led activities happening in their mathematics lessons.

4 Do I have to take part?

It is completely up to you whether or not you decide to allow your child to take part in this study. If you do decide for your child to take part, you will be given this information sheet to keep and be asked to sign a consent form. Agreeing for your child to join the study does not mean that your child has to complete it. Your child is free to withdraw at any stage without giving a reason. A decision to withdraw at any time, or a decision not to take part at all, will not affect any treatment/care that your child may receive (should this be relevant).

5 **Are there any age or other restrictions that may prevent me from participating?**

To be included in the study, your child is required to be between the ages of 12 to 18 years, deaf and have the ability to understand and take part in the required assessments and activities. Your child will be excluded if they have not taken part in enough of the intervention program due to lack of attendance set at 80%.

6 **How long will my part in the study take?**

If your child decides to take part in this study, they will be involved in it for the 2024/25 autumn school term.

7 **What will happen to me if I take part?**

The first thing to happen will be that your child be asked to complete some tasks as part of the pre-assessment stage of this programme. These will include a working memory task which will involve your teacher speaking/signing some information, and your child speaking/signing it back, and a computer/tablet activity. When the pre assessment is complete, your child will begin the intervention programme.

At the beginning of each mathematics lesson, your child will take part in a starter activity where they would be required to remember numbers and pictures. Some activities are independent, and some teacher-led. The activities will last for approximately 10 to 15 minutes. The intervention programme will run for ten weeks.

At the end of the intervention programme, your child will need to complete the same tasks as they did for the pre-assessment stage.

8 **What are the possible disadvantages, risks or side effects of taking part?**

There are no possible disadvantages, risks or side effects from taking part in this study.

9 **What are the possible benefits of taking part?**

By taking part in the intervention programme, it is possible that your child can improve their attention and working memory. That can lead to improved learning in mathematics.

10 **How will my taking part in this study be kept confidential?**

All the detailed information that is collected from the completed consent forms will be placed in a folder, and locked in a secure cupboard in the school premises, where only the researcher (Mr. Lee) will have access to. All identifiable information linked to the study (full name, contact details and consent forms) will be stored for the duration of the study and destroyed upon completion of the study.

12 What will happen to the data collected within this study?

- The collected data will be stored electronically in a password-protected environment for the duration of the study. After this period, it will be securely destroyed. Specifically, all study data will be securely stored on my university OneDrive cloud storage system, accessible only to me (and my supervisor(s). The data will be deleted as per the specified timeline.
- The data will be anonymised/pseudonomised prior to storage.
- The data will be transmitted/displayed in reports, conferences, and presentations to school members during which all data will remain anonymised.

13 Will the data be required for use in further studies?

- The data collected may be re-used or subjected to further analysis as part of a future ethically-approved study; the data to be re-used will be anonymised.
- The results of the study and/or the data collected (in anonymised form) may be deposited in an open access repository.

14 Who has reviewed this study?

This study has been reviewed by:

- The University of Hertfordshire Social Sciences, Arts and Humanities Ethics Committee with Delegated Authority

The UH protocol number is < **0517 2025 Jan SSAH**>

15 Factors that might put others at risk

Please note that if, during the study, any medical conditions or non-medical circumstances such as unlawful activity become apparent that might or had put others at risk, the University may refer the matter to the appropriate authorities and, under such circumstances, your child will be withdrawn from the study.

16 Who can I contact if I have any questions?

If you would like further information or would like to discuss any details personally, please get in touch with me, in writing, by phone or by email: Sai Lee, [redacted]. Alternatively, you may want to discuss with my supervisor by email: Lisa Bull, [redacted]

Although we hope it is not the case, if you have any complaints or concerns about any aspect of the way you have been approached or treated during the course of this study, please write to the University's Secretary and Registrar at the following address:

University of Hertfordshire UH Ethics Committee

Secretary and Registrar
University of Hertfordshire
College Lane
Hatfield
Herts
AL10 9AB

Thank you very much for reading this information and giving consideration to taking part in this study.

iii. Participant Information Sheet (Learners aged 16 – 17)

University of Hertfordshire UH Ethics Committee

UNIVERSITY OF HERTFORDSHIRE

ETHICS COMMITTEE FOR STUDIES INVOLVING THE USE OF HUMAN PARTICIPANTS ('ETHICS COMMITTEE')

PARTICIPANT INFORMATION SHEET (ADULTS 16+)

1 Title of study

A feasibility study in an intervention programme to support deaf learners in improving their working memory

2 Introduction

You are being invited to take part in a Master's study. Before you decide whether to do so, it is important that you understand the study that is being undertaken and what your involvement will include. Please take the time to read the following information carefully and discuss it with others if you wish. Do not hesitate to ask us anything that is not clear or for any further information you would like to help you make your decision. Please do take your time to decide whether or not you wish to take part. The University's regulation, UPR RE01, 'Studies Involving the Use of Human Participants' can be accessed via this link:

https://www.herts.ac.uk/about-us/governance/university-policies-and-regulations-uprs/uprs (after accessing this website, scroll down to Letter S where you will find the regulation)

Thank you for reading this.

3 What is the purpose of this study?

Previous studies have suggested that deaf learners might experience difficulties with their working memory. Since working memory is important in storing short term memories and manipulating information, weaker working memory can impact the their ability to learn mathematics. The purpose of this study is to find out how effective an intervention programme is, in supporting deaf learners to improve their working memory. In the programme, you will have the opportunity to practice and train their working memory through interactive games and teacher led activities happening in their mathematics lessons.

4 Do I have to take part?

It is completely up to you whether or not you decide to take part in this study. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. Agreeing to join the study does not mean that you have to complete it. You are free to withdraw at any stage without giving a reason. A decision to withdraw at any time, or a decision not to take part at all, will not affect any treatment/care that you may receive (should this be relevant).

5 Are there any age or other restrictions that may prevent me from participating?

To be included in the study, you are required to be between the ages of 12 to 18 years, deaf and have the ability to understand and take part in the required assessments and activities.

You will be excluded if you have not taken part in enough of the intervention program due to lack of attendance set at 80%.

6 **How long will my part in the study take?**

If you decide to take part in this study, you will be involved in it for the 2024/25 autumn school term.

7 **What will happen to me if I take part?**

The first thing to happen will be that you will be asked to complete some tasks as part of the pre-assessment stage of this programme. These will include a working memory task which will involve your teacher speaking/signing some information, and you speaking/signing it back, and a computer/tablet activity. When the pre assessment is complete, you will begin the intervention programme.

At the beginning of each mathematics lesson, you will take part in a starter activity where you would be required to remember numbers and pictures. Some activities are independent, and some teacher-led. The activities will last for approximately 10 to 15 minutes. The intervention programme will run for ten weeks.

At the end of the intervention programme, you will need to complete the same tasks as you did for the pre-assessment stage.

8 **What are the possible disadvantages, risks or side effects of taking part?**

There are no possible disadvantages, risks or side effects from taking part in this study.

9 **What are the possible benefits of taking part?**

By taking part in the intervention programme, it is possible that you can improve your attention and working memory. That can lead to improved learning in mathematics too.

10 **How will my taking part in this study be kept confidential?**

All the detailed information that is collected from the completed consent forms will be placed in a folder, and locked in a secure cupboard in the school premises, where only the researcher will have access to. All identifiable information linked to the study (full name, contact details and consent forms) will be stored for the duration of the study and destroyed upon completion of the study.

12 **What will happen to the data collected within this study?**

- The collected data will be stored electronically in a password-protected environment for the duration of the study. After this period, it will be securely destroyed. Specifically, all study data will be securely stored on my university OneDrive cloud storage system, accessible only to me (and my supervisor(s). The data will be deleted as per the specified timeline.

- The data will be anonymised/pseudonomised prior to storage.

- The data will be transmitted/displayed in reports, conferences, and presentations to school members during which all data will remain anonymised.

13 Will the data be required for use in further studies?

- The data collected may be re-used or subjected to further analysis as part of a future ethically-approved study; the data to be re-used will be anonymised.

- The results of the study and/or the data collected (in anonymised form) may be deposited in an open access repository.

14 Who has reviewed this study?

This study has been reviewed by:

- The University of Hertfordshire Social Sciences, Arts and Humanities Ethics Committee with Delegated Authority

The UH protocol number is **0517 2025 Jan SSAH**

15 Factors that might put others at risk

Please note that if, during the study, any medical conditions or non-medical circumstances such as unlawful activity become apparent that might or had put others at risk, the University may refer the matter to the appropriate authorities and, under such circumstances, you will be withdrawn from the study.

16 Who can I contact if I have any questions?

If you would like further information or would like to discuss any details personally, please get in touch with me, in writing, by phone or by email: Sai Lee, [redacted] Alternatively, you may want to discuss with my supervisor by email: Lisa Bull, [redacted]

Although we hope it is not the case, if you have any complaints or concerns about any aspect of the way you have been approached or treated during the course of this study, please write to the University's Secretary and Registrar at the following address:

Secretary and Registrar
University of Hertfordshire
College Lane
Hatfield
Herts
AL10 9AB

University of Hertfordshire UH Ethics Committee

Thank you very much for reading this information and giving consideration to taking part in this study.

iv. Participant Information Sheet (Learners aged 12 to 15)

UNIVERSITY OF HERTFORDSHIRE

ETHICS COMMITTEE FOR STUDIES INVOLVING THE USE OF HUMAN PARTICIPANTS ('ETHICS COMMITTEE')

PARTICIPANT INFORMATION SHEET (CHILDREN)

1 Title of study

A feasibility study in an intervention programme to support deaf learners in improving their working memory

2 Introduction

You are being invited to take part in a university study. Before you agree, you must understand what it is about and how you are involved. You can discuss this with your parents or careers. If you do not understand it, you can speak to the researcher (Mr. Lee) who can explain it to you. Take your time to think if you would like to join in the study.

3 What is the purpose of this study?

Research has suggested that deaf learners may have difficulties with their working memory. Because working memory is important in remembering things and using them, weaker working memory can make learning mathematics difficult. The researcher (Mr. Lee) wants to find out if playing memory games can help deaf learners improve their working memory. In your mathematics lessons, you can practice and train your working memory by playing these games.

4 Do I have to take part?

If you want to take part, you will be given this information sheet to keep and be asked to sign a consent form. Taking part means that any test data collected can be used for the study. If you do not take part in this study, you will still take part in the activities, but your data will not be used in the study. You can choose to leave the study at any time.

5 Are there any age or other restrictions that may prevent me from participating?

To take part in the study, you need to be between 12 to 18 years old. You must be deaf and be able to understand and take part in the tests and activities. Your data will not be used in the study if you miss too many lessons.

6 How long will my part in the study take?

If you take part in this study, you will be involved in it for the 2024/25 autumn term.

7 What will happen to me if I take part?

You will be asked to do some tests at the beginning. These involve repeating back information that the teacher has signed or spoken to you. Another test involves pressing shapes on the computer or tablet screen in the same way it was presented to you. When the tests are complete, you will begin the memory games.

In your Mathematics lessons, you will take part in some memory games, where you would be required to remember numbers and pictures. Some activities are done by yourself, and some with you teacher. The games are about 10 to 15 minutes long and will go on for ten weeks.

When the ten weeks have finished, you will need to complete the same test as you did at the beginning.

8 What are the possible disadvantages, risks or side effects of taking part?

There are no disadvantages, risks or side effects by taking part in this study.

9 What are the possible benefits of taking part?

By joining this study, you may improve your attention and working memory. That means your learning of mathematics may improve too.

10 How will my taking part in this study be kept confidential?

All the data that is collected from your consent forms will be placed in a folder, and locked in a secure cupboard in school. Only the researcher (Mr. Lee) can see it. This data will be destroyed when the study has finished.

12 What will happen to the data collected within this study?

- The data that is stored in a computer, will be protected using password. After the study has finished, it will be destroyed. Any data stored on the researchers (Mr. Lee's) university computer system, can only be seen by Mr. Lee and his supervisor.
- The data stored will not have any names in it, and they cannot be linked to you.
- Any presentations linked to the study will not use your name.

13 Will the data be required for use in further studies?

- The data collected may be re-used in a future ethically-approved study
- When complete, the study and the data collected (without any names) may be read by other people interested learning about this study

University of Hertfordshire UH Ethics Committee

14 Who has reviewed this study?

This study has been reviewed by:

The University of Hertfordshire Social Sciences, Arts and Humanities Ethics Committee with Delegated Authority

The UH protocol number is < **0517 2025 Jan SSAH** >

15 Factors that might put others at risk

Please note that during the study, any medical conditions or non-medical circumstances such as unlawful activity become apparent that might or had put others at risk, the University may refer the matter to the appropriate authorities and, under such circumstances, you will be withdrawn from the study.

16 Who can I contact if I have any questions?

If you would like further information or would like to discuss any details personally, please get in touch with me, in writing, by phone or by email: Sai Lee, [redacted]. Alternatively, you may want to discuss with my supervisor by email: Lisa Bull, [redacted]

Although we hope it is not the case, if you have any complaints or concerns about any aspect of the way you have been approached or treated during the course of this study, please write to the University's Secretary and Registrar at the following address:

Secretary and Registrar
University of Hertfordshire
College Lane
Hatfield
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Thank you very much for reading this information and giving consideration to taking part in this study.

v. Consent Form (Parents and Carers)

University of Hertfordshire UH Ethics Committee

UNIVERSITY OF HERTFORDSHIRE
ETHICS COMMITTEE FOR STUDIES INVOLVING THE USE OF HUMAN PARTICIPANTS
('ETHICS COMMITTEE')

CONSENT FORM FOR STUDIES INVOLVING HUMAN PARTICIPANTS

I, the undersigned *[please give your name here, in BLOCK CAPITALS]*

....

of *[please give contact details here, sufficient to enable the investigator to get in touch with you, such as a postal or email address]*

....

hereby agree to allow my child to take part in the study entitled 'A Feasibility Study in an Intervention Program to support Improvement in the Working Memory of Deaf Children'

UH Protocol number: **0517 2025 Jan SSAH**)

1 I confirm that I have been given a Participant Information Sheet (a copy of which is attached to this form) giving particulars of the study, including its aim(s), methods and design, the names and contact details of key people and, as appropriate, the risks and potential benefits, how the information collected will be stored and for how long, and any plans for follow-up studies that might involve further approaches to participants. I have also been informed of how their personal information on this form will be stored and for how long. I have been given details of their involvement in the study. I have been told that in the event of any significant change to the aim(s) or design of the study I will be informed, and asked to renew my consent for them to participate in it.

2 I have been assured that they may withdraw from the study at any time without disadvantage or having to give a reason.

3 I have been told how information relating to my child (data obtained in the course of the study, and data provided by them about themself) will be handled: how it will be kept secure, who will have access to it, and how it will or may be used, as well as how it is going to be stored.

4 I understand that if there is any revelation of unlawful activity or any indication of non-medical circumstances that would or has put others at risk, the University may refer the matter to the appropriate authorities.

5 I understand that their information may be subject to review by possible individuals from the University for monitoring purposes.

6 I agree that the anonymised research data may be used by others for future research. [No one will be able to identify them when the data is shared]

7 I understand that the information they have submitted will be published as a report.

8 I confirm that I am happy for my child to participate in this study.

Signature of parent..Date.................................

Participant Consent Form - 6 January 2025

Signature of (principal) investigator………………………………………………………Date…………………………

Name of (principal) investigator: MR C S H LEE

vi. Consent Form (Learners aged 18+)

University of Hertfordshire UH Ethics Committee

UNIVERSITY OF HERTFORDSHIRE
ETHICS COMMITTEE FOR STUDIES INVOLVING THE USE OF HUMAN PARTICIPANTS
('ETHICS COMMITTEE')

CONSENT FORM FOR STUDIES INVOLVING HUMAN PARTICIPANTS

I, the undersigned *[please give your name here, in BLOCK CAPITALS]*

………

of *[please give contact details here, sufficient to enable the investigator to get in touch with you, such as a postal or email address]*

………

hereby freely agree to take part in the study entitled 'A Feasibility Study in an Intervention Program to support Improvement in the Working Memory of Deaf Children'

(UH Protocol number: **0517 2025 Jan SSAH**)

1 I confirm that I have been given a Participant Information Sheet (a copy of which is attached to this form) giving particulars of the study, including its aim(s), methods and design, the names and contact details of key people and, as appropriate, the risks and potential benefits, how the information collected will be stored and for how long, and any plans for follow-up studies that might involve further approaches to participants. I have also been informed of how my personal information on this form will be stored and for how long. I have been given details of my involvement in the study. I have been told that in the event of any significant change to the aim(s) or design of the study I will be informed, and asked to renew my consent to participate in it.

2 I have been assured that I may withdraw from the study at any time without disadvantage or having to give a reason.

3 I have been told how information relating to me (data obtained in the course of the study, and data provided by me about myself) will be handled: how it will be kept secure, who will have access to it, and how it will or may be used, as well as how it is going to be stored.

4 I understand that if there is any revelation of unlawful activity or any indication of non-medical circumstances that would or has put others at risk, the University may refer the matter to the appropriate authorities.

5 I understand that my information may be subject to review by possible individuals from the University for monitoring purposes.

6 I agree that the anonymised research data may be used by others for future research. [No one will be able to identify you when the data is shared]

7 I understand that the information I have submitted will be published as a report.

8 I confirm that I am happy to participate in this study.

Signature of participant…………………………………………………… Date……………………………

Signature of (principal) investigator…………………………………………… Date……………………………

Name of (principal) investigator: MR C S H LEE

vii. Assent Form (Learners aged 16 to 17)

University of Hertfordshire UH Ethics Committee

UNIVERSITY OF HERTFORDSHIRE
ETHICS COMMITTEE FOR STUDIES INVOLVING THE USE OF HUMAN PARTICIPANTS
('ETHICS COMMITTEE')

CONSENT FORM FOR STUDIES INVOLVING HUMAN PARTICIPANTS

I, the undersigned *[please give your name here, in BLOCK CAPITALS]*

………………………………………………………………………………………………………

of *[please give contact details here, sufficient to enable the investigator to get in touch with you, such as a postal or email address]*

………………………………………………………………………………………………………

hereby freely agree to take part in the study entitled 'A Feasibility Study in an Intervention Program to support Improvement in the Working Memory of Deaf Children'

(UH Protocol number: **0517 2025 Jan SSAH**)

1 I confirm that I have been given a Participant Information Sheet (a copy of which is attached to this form) giving particulars of the study, including its aim(s), methods and design, the names and contact details of key people and, as appropriate, the risks and potential benefits, how the information collected will be stored and for how long, and any plans for follow-up studies that might involve further approaches to participants. I have also been informed of how my personal information on this form will be stored and for how long. I have been given details of my involvement in the study. I have been told that in the event of any significant change to the aim(s) or design of the study I will be informed, and asked to renew my consent to participate in it.

2 I have been assured that I may withdraw from the study at any time without disadvantage or having to give a reason.

3 I have been told how information relating to me (data obtained in the course of the study, and data provided by me about myself) will be handled: how it will be kept secure, who will have access to it, and how it will or may be used, as well as how it is going to be stored.

4 I understand that if there is any revelation of unlawful activity or any indication of non-medical circumstances that would or has put others at risk, the University may refer the matter to the appropriate authorities.

5 I understand that my information may be subject to review by possible individuals from the University for monitoring purposes.

6 I agree that the anonymised research data may be used by others for future research. [No one will be able to identify you when the data is shared]

7 I understand that the information I have submitted will be published as a report.

8 I confirm that I am happy to participate in this study.

Signature of participant………………………………………………………… Date…………………………

Participant Assent Form - 6 January 2025

Signature of (principal) investigator……………………………………………………. Date…………………………….

Name of (principal) investigator: MR C S H LEE

viii. Assent Form (Learners aged 12 to 15)

University of Hertfordshire UH Ethics Committee

UNIVERSITY OF HERTFORDSHIRE
ETHICS COMMITTEE FOR STUDIES INVOLVING THE USE OF HUMAN PARTICIPANTS
('ETHICS COMMITTEE')

CONSENT FORM FOR STUDIES INVOLVING HUMAN PARTICIPANTS

I, *[please give your name here, in BLOCK CAPITALS]*

……

hereby freely agree to take part in the study entitled 'A Feasibility Study in an Intervention Program to support Improvement in the Working Memory of Deaf Children'

(UH Protocol number: **0517 2025 Jan SSAH**)

1 I confirm that I have been given a Participant Information Sheet (a copy is attached) which explains what you will be asked to do and why by your researcher (Mr. Lee). I have had the opportunity to ask questions and receive answers that I have understood.

2 I understand that I do not have to take part and if I decide that I want to stop taking part in this study I can stop at any time without giving any reason.

3 I have been told how information relating to me (such as my name and date of birth) will be used.

4 I understand that if there is any revelation of unlawful activity or any indication of non-medical circumstances that would or has put others at risk, the University may refer the matter to the appropriate authorities

5 I agree that the results of the study can be published and shared with other researchers, teachers, and other staff, but only after they have been fully anonymised (meaning that no one will know who you are)

6 I understand that all the information collected about me will only be seen by researchers working on this study and nobody else (will stay confidential)

7 I am happy to participate in this study.

Signature of participant……………………………………………………Date…………………………

Name of parent/carer *[in BLOCK CAPITALS please]*

……………………………………………………………………………………………………

Signature of (principal) investigator……………………………………………………Date…………………………

Name of (principal) investigator: MR C S H LEE

Participant Consent Form – 6 January 2025

ix. Forward Digit Span Record Sheet

[Redacted due to copyright]

x. Backward Digit Span Record Sheet

[Redacted due to copyright]

xi. Corsi Block Tapping Test Record Sheet

Corsi Block Assessment   Student ID:

Item	Block Length achieved	Block Length	Response	Library Entry Number	Trial Score	Item Score
1.		2			0 1	0 1 2
		2			0 1	
2.		3			0 1	0 1 2
		3			0 1	
3.		4			0 1	0 1 2
		4			0 1	
4.		5			0 1	0 1 2
		5			0 1	
5.		6			0 1	0 1 2
		6			0 1	
6.		7			0 1	0 1 2
		7			0 1	
7.		8			0 1	0 1 2
		8			0 1	
8.		9			0 1	0 1 2
		9			0 1	

Longest Span

Total Correct Trials

(Maximum = 16)