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The ontogeny of visual motor memory and its importance in handwriting and reading: A developing construct

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Summary

Humans have evolved a remarkable ability to remember visual shapes and use these representations to generate motor activity (from Palaeolithic cave drawings through Jiahu symbols to cursive handwriting). The term Visual Motor Memory describes this psychological ability, which must have conveyed an evolutionary advantage and which remains critically important to humans (e.g. when learning to write). Surprisingly little empirical investigation of this unique human ability exists - almost certainly because of the technological difficulties involved in measuring VMM. We deployed a novel technique for measuring this construct in 87 children (6-11 years old, 44 females). Children drew novel shapes presented briefly on a tablet laptop screen, drawing their responses from memory on the screen using a digitiser stylus. Sophisticated algorithms (using point-registration techniques) objectively quantified the accuracy of the children's reproductions. VMM performance improved with age and with less complex shapes, indicating that the measure captured meaningful developmental changes. The relationship between VMM and scores on nationally standardised writing assessments were explored with the results showing a clear relationship between these measures, even after controlling for age. Moreover, a relationship between VMM and the nationally standardised reading test was mediated via writing ability, suggesting VMM's wider importance within language development.

Keywords: Language development; Memory; Motor Activity; Handwriting; Reading

Introduction

An important evolutionary advantage is conferred to humans via their unique ability to communicate across time and space through the transmission of manually produced symbols (e.g. writing) [1]. Thus, gaining insight into the development of the underpinning cognitive processes that have evolved to enable humans to use writing-systems for communication is of great interest in understanding the ontogeny of this unique human ability. Moreover, the ability to produce and interpret written symbols remains an essential part of every child's development.

The component skills that enable the motor activity of picking up a pen or pencil and drawing an alphanumeric symbol are both complex and diverse [2]. Nonetheless, the fundamental challenge is one of learning how to generate motor commands that result in an effector (the hand) producing a graphical representation of a memorised shape (alphanumerical symbol). Thus, learning to write is contingent on a cognitive ability to remember visual patterns and recruit the appropriate neural circuit to translate these patterns from memory to page. We define this psychological process as 'Visual Motor Memory' for symbolic representations (i.e. memory of a visual pattern and how to reproduce an approximation of the shape via the motor system).

We predicted that Visual Motor Memory (VMM) must underpin the procedural aspects of learning to write and hypothesised that this cognitive skill is the pathway through which increased automaticity in handwriting emerges with practice. Namely, as individuals practise they become quicker to recall and execute the commands necessary to produce legible letter/word forms [3]. It also follows that this 'routinising' should free up more cognitive resources for more abstract higher-order language processes (e.g. composition, syntax, spelling), which develop concurrently with learning to write [3,4]. Thus, it is plausible that VMM ability may indirectly influence the rate of development of these non-motoric language processes.

Furthermore, based on an embodied theory of cognition [5], we hypothesised that VMM ability should affect written language recognition, as well as influencing written language production. In other words, VMM should also support reading abilities. Indeed, it is probable that more practiced and procedural recall of letter/word forms whilst writing could aid pattern recognition when reading. This proposal is supported by evidence showing that the motor processes associated with writing reinforce a child's ability to recognise alphanumerical symbols [6]. Longcamp et al [7] have demonstrated the importance of learning the motor representations of symbols for later visual recognition in adults. They taught participants new characters taken from the Gujarati or Bengali alphabets: half were trained using a typewriter and half by copying the characters by hand. Participants in the handwriting group were better able to recognise the new characters and retained this improved memory over time. Longcamp, Zerbato-Poudou and Velay [8] found improvement for character recognition in five year olds when they learnt the letters through copying compared with typing, whilst Naka [9] showed that repeated writing of Chinese or Arabic characters by Japanese primary school children led to increased recall compared to just looking at the characters. Most recently, brain-imaging research has suggested that in pre-literate children the neural pathways associated with reading only activate in response to viewing letters if a child has previously been trained to print these letters free-form, as opposed to tracing their outline or typing them on a keyboard [10]. This implies that the activity of handwriting (and VMM) is advantageous for reading because it facilitates deeper knowledge of the component features that constitute a letter's form, aiding children's ability to distinguish and categorise letters.

To date, it has not been possible to test the hypothesised importance of visual motor memory (VMM) to handwriting skill or explore the possibility that VMM may play a role in wider aspects of language development. This is because technological limitations have meant it has not been possible to measure an individual's ability to graphically reproduce a shape, in sufficient detail, to justify a rigorous scientific investigation of this ability. For example, the Alphabet Writing component of the Written Expression subscale of the Wechsler Individual Achievement Test (WIAT-II) [11] requires children to write the letters of the alphabet on lined paper for thirty seconds. These letters are then assessed visually by researchers and scored on the basis of factors such as alignment and proportionality [e.g. 12]. Swanson and Berninger [13] assessed handwriting by asking children to copy a portion of text and then visually examining it to award points for whether or not individual words were legible. These techniques are inappropriately subjective for a scientific investigation of VMM. Widely used standardised assessments of general fine-motor control skills also assess children's manipulation of a stylus in coarse ways. The Beery-Buktenica test of Visuo-Motor Integration [14], widely used to assess handwriting difficulties in children [15], only judges an individual's ability to copy a set of abstract shapes on a set of pass/fail criteria. These types of subjective and categorical measurements are not able to account for subtle differences in the ability to reproduce a pattern from memory using a stylus (i.e. the core functional challenge in handwriting) and will thus inevitably produce unsophisticated estimations of handwriting ability.

Fortunately, recent innovations have allowed researchers to utilise digital tablets to record children's handwriting and (more generally) stylus manipulation skills with precision [16–19]. One such system, developed by Culmer, Levesley, Mon-Williams and Williams [20], uses specialist software to capture kinematic data via a tablet laptop, with the screen acting as the writing surface and a digitiser stylus as the pen (the digital equivalent of using a pen with paper). This technology has been used to present two-dimensional line-drawing stimuli on the screen, which participants either need to trace over or simultaneously copy on another area of the screen. Robust point-set registration methods can then be used to post-process the participant's drawings to generate error scores that provide objective measurements of the participants' ability to accurately trace/copy the stimuli presented [21,22]. This is exactly the type of technique required to capture meaningful measures of VMM ability. Using such a testing system, participants can be asked to reproduce (from memory) shapes previously presented on the tablet's screen, providing a direct and objective assessment of VMM.

We therefore set up the following cross-sectional study to measure this ability in a sample of school-aged children (6-11 years old). We examined whether this skill related to and underpinned children's writing ability and whether it contributed to their reading skill. We addressed these issues by relating VMM scores to UK standardised scores of the children's writing and reading ability supplied by the school. We predicted a relationship between VMM and children's writing ability that would mediate a further relationship between children's writing and reading abilities.

Method

Participants

An opportunity sample of eighty-seven children (44 females) was recruited from a primary school in West Yorkshire: 33 from Year 2 (age range 6.7-7.7 years, M = 7.1), 27 from Year 4 (8.5-9.4 years, M = 8.9), and 27 from Year 6 (10.6-11.5 years, M = 11.0). Gender was approximately equally split across each age group. Eight percent of participants were left-handed, also evenly distributed across all groups. All participants had English as their first language, had normal vision or corrected to normal vision, and no history of neurological disorder. Ethical approval for the study was obtained from the University of Leeds Research Ethics Committee and the research was carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki.

Apparatus

A specialised software programme presented visual stimuli whilst simultaneously recording participants' kinematic responses via a hand-held stylus [20]. The software platform was used on a tablet computer (Toshiba Portege M700-13P tablet, screen: 260x163mm, 1200x800 pixels, 60 Hz refresh rate), with the screen digitiser measuring planar position of the stylus at a rate of 120 Hz, allowing precise measurements of complex movement to be reliably captured.

Procedure

To measure visual motor memory (VMM) participants were seated comfortably at a table, and the tablet laptop screen was rotated 180 degrees and folded down to create a horizontal 'writing surface' in front of them. Participants used the pen-shaped digitising stylus as an input device to interact with the screen.

The VMM task required participants to place the stylus on a circle at the bottom of the screen. This subsequently caused a shape to appear on screen for three seconds then disappear. Upon the shape disappearing participants then had to reproduce the observed shape as accurately as possible. They drew their reproduction between two dots presented on the screen and were instructed to starting drawing from the left and finish at the right (see Figure 1). The shapes were square waves of varying complexity: complexity was varied by altering height and/or width of the wave. For low complexity the waves had the same height and width; for medium complexity the waves differed in one dimension (either height *or* width); and for high complexity the waves differed in both dimensions. Thus as a shape's complexity increased so the number of unique parameters (i.e. lengths of horizontal and vertical straight lines) needing to be stored in memory increased.

There were twenty trials in total: the first two were practice trials and therefore not included in the final analyses. Children's baseline motor skills were measured via a copying task using an additional set of square waves where the shape remained in the top half of the screen whilst participants copied it in the bottom (i.e. no memory component). The copying task was always administered before the main task, with a short break between the two. Writing and Reading scores (on a numerical scale) standardised against national norms were provided by the school.

Analysis

For each VMM trial the accuracy with which participant's drawing (their input path) depicted the target shape (the reference path) was evaluated using the following procedure: point-sets were generated for the input and reference paths by discarding temporal information and resampling the X and Y coordinates at a spatial resolution of 1mm using linear interpolation. A robust point-registration method [23] was then used to determine the rigid transformation (consisting of translation, rotation and isotropic scaling components) which best transformed the input path to match the reference path. A metric, Optimised Error (OE), was then calculated to represent the ability to accurately reproduce the target shape by quantifying the congruence between input and target shapes. This was determined by evaluating the mean distance between corresponding points in the transformed input and reference path [21] and was thus independent of the scaling and rotation artefacts involved in the shape reproduction.

For statistical analysis, OE was taken as a measure of visual motor memory (VMM) and specified as the dependent variable in a repeated measures ANOVA with Age categorised by School Year (year 2; year 4; year 6) and Shape Complexity (low, medium, high) specified as independent variables. Correlational analyses were then conducted on the visual-motor memory task and writing & reading performance measurements, followed by a linear regression analysis. An anonymised version of the dataset is available through Dryad (http://datadryad.org/), unique DOI: XXX (data to be uploaded if manuscript accepted for publication as per Proc R. Soc instructions).

Results

VMM (OE) was the dependent variable in a 3 (Age) x 3 (Shape Complexity) mixed measures ANOVA ($\alpha = 5\%$). There was a main effect of Age, $F(2, 85) = 27.1$, $\eta_p^2 = .39$, (error decreasing with increasing age), and a main effect of Shape Complexity, $F(2, 170) = 166.6$, $\eta_p^2 = .66$, (error increasing with increasing shape complexity). Post-hoc analyses showed all age groups and all three levels of shape complexity differed significantly from each other (see Figure 2). The interaction between these main effects was not statistically significant.

In order to obtain an overall measure of each participant's VMM ability, a composite measure was obtained by calculating each participant's mean average Optimised Error score across the three levels of shape-complexity. A partial correlation was run between VMM, writing and reading, controlling for age and baseline motor ability (i.e. Copying: OE). VMM was correlated with writing ($r = -.42$, $p<.001$) and reading ($r = -.32$, $p<.01$), and writing and reading were correlated ($r = .53$, $p<.001$). A regression analysis was run with writing as the dependent variable. Age (in months) & Copying were entered in Step 1, and VMM entered in Step 2. The model at Step 1 was significant, $F(1, 87) = 157.7$, $p<.001$. The model at Step 2 made an additional significant contribution ($\Delta R^2 = .06$, $p<.001$), with VMM a unique predictor of Writing, $\beta = -.31$, $t(87) = -4.22$, $p<.001$. The same hierarchical regression was run with Reading as the dependent variable. The model at Step 2 made an additional significant contribution ($\Delta R^2 = .04$, $p<.01$) and VMM was again a unique and significant predictor ($\beta = -.21$, $t(87) = -3.10$, $p<.01$). To test whether writing mediated this relationship a second regression analysis was conducted where Writing was also entered in Step 1, and VMM in Step 2. The model at Step 2 no longer made an additional contribution ($\Delta R^2 = .003$, $p>.05$). The

Sobel test [24] confirmed that the indirect effect of VMM on Reading via Writing was significant (z = -3.39, p<.001).

Discussion

We have successfully developed an objective technique for studying Visual Motor Memory (VMM) and have found evidence in support of the notion that this cognitive process is an important construct underpinning both handwriting and reading ability in children. VMM provides a plausible cognitive pathway through which the motor aspects of handwriting can become more automated, reducing the cognitive load of the procedural aspects of this activity and freeing resources for the development of higher order language skills [4]. This proposal is supported by the indirect effect of VMM on academic reading scores (through its relationship with academic writing scores) and is consistent with previous evidence of motor representations of letters reinforcing visual letter recognition in children [8–10].

The validity of viewing VMM as a distinct cognitive process (i.e. not purely motoric) is corroborated by the fact that the results show principled alterations in response to age and shape-complexity whereby increased cognitive maturity with age positively affects VMM functioning but increased memory demands (linked to increasing shape-complexity) have an opposing negative effect. Further support for VMM as a meaningful construct can be found in the wider literature. For example, it is known that visual memory skills predict the abilities of individuals who use drawing in a professional capacity to communicate ideas - such as college students of art [25] and technical drawing [26]. It is logical to suggest that the role for visual memory in drawing is analogous to the one we have identified for VMM within handwriting. Artists and draughtsman rely on memory to represent often encountered patterns/angles (e.g. when constructing compositions or laying out schematics) and thus the automaticity with which they can access such representations will doubtless have a bearing on their drawing's quality.

On this basis, we propose that VMM is a core cognitive ability that influences the ability to use any form of communication via visual symbols.

The concept of VMM is also in keeping with current theories on the embodied nature of cognition [5] – in that basic perceptual and motor control processes must inform the development of higher-order cognitive abilities, such as communication skills. Nonetheless, further empirical investigation is required: longitudinal research looking at whether rate of language acquisition (writing and reading) is mediated by VMM ability would help increase our understanding of the degree to which VMM contributes to writing and reading development. In addition, research across a wider age range might be expected to find the strength of the relationship between VMM and language abilities varying with time. Specifically, once automaticity of handwriting rises above a certain threshold it might be expected that the relative contribution of VMM to wider language ability will diminish [3].

This research opens up the exciting possibility of identifying children at risk of problems in the domains of reading and writing, given that children who performed less well on the VMM task were more likely to have lower scores on national school-based writing and reading tests. Empirical evidence already suggests that in pre-school children nascent handwriting ability is associated with concurrent levels of emergent literacy skill [27,28], indexed by letter identification and word decoding abilities. Meanwhile, within schools there is evidence of a link between the automaticity of children's handwriting (between 7 and 11 years old) and the quality of composition within written work [29,30]. If VMM is the cognitive process within which the critical shift from effortful to proceduralised/automatic production of letters occurs [3] then we have identified a key cognitive component, potentially amenable to intervention, that underpins the early stages of written language acquisition.

In summary, we have presented a new method for exploring the factors that contribute to the successful formation and use of a visual-motor code in memory. We have used this method to investigate a hypothesised cognitive construct (VMM) that we believe is a central component facilitating handwriting and wider literacy development. This sheds light on an important cognitive process that underpins one of the unique evolutionary advantages possessed by humans – the ability to learn and use complex writing-systems in order to store and disseminate information [1].

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Data Accessibility

The anonymised dataset of individual participant's data on all outcomes and predictors will be uploaded to data Dryad and will be publicly available to access immediately upon publication.

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Figure Captions

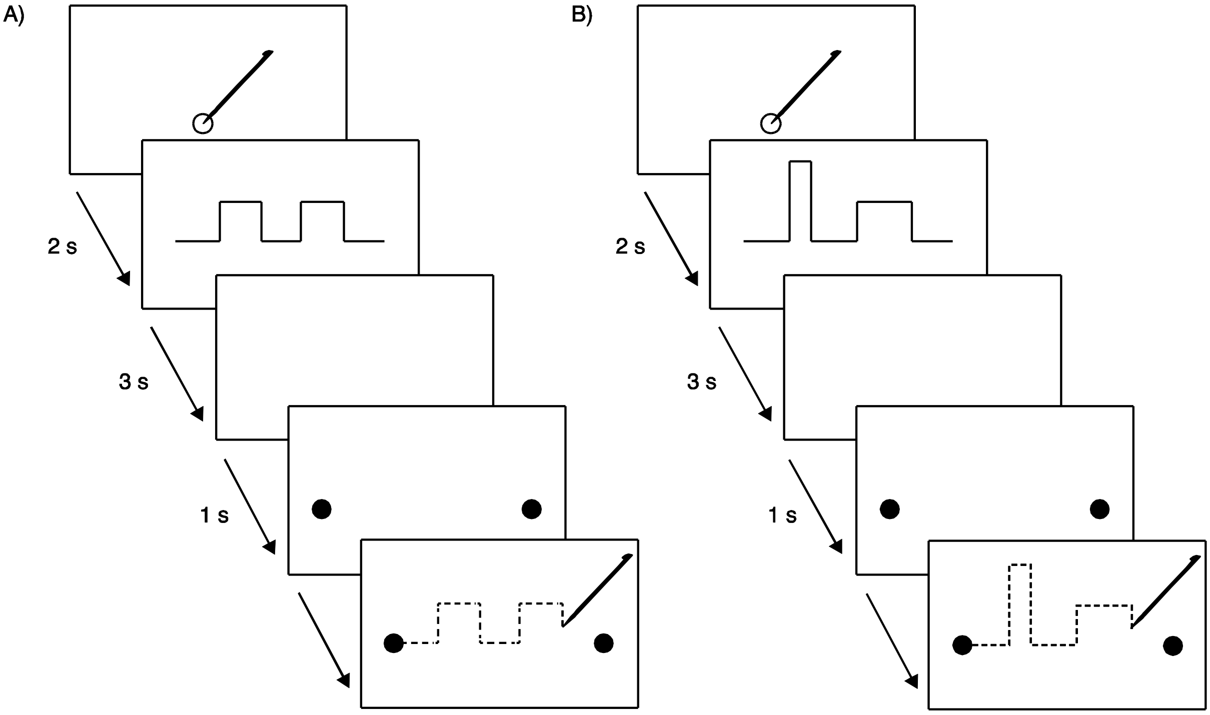

Figure 1. Depiction of the Visual Motor Memory Task (VMM). Sequence A depicts an example of a trial presenting a low complexity shape (i.e. the two square-waves' heights and widths are both equal). Sequence B an example of a trial presenting a high complexity shape (i.e. the two square-waves' heights and widths both differ). Moving top to bottom within each sequence (i.e. following arrows) the time course of a trial was as follows: participants placed their stylus within a circle on an otherwise blank screen to commence trial; target shape was presented on-screen for 3 seconds; 1 second blank-screen interval followed; parallel ‘start’ and ‘end’ point dots appear on screen; participants completed trial by drawing their reproduction of the target shape from left to right between the dots.

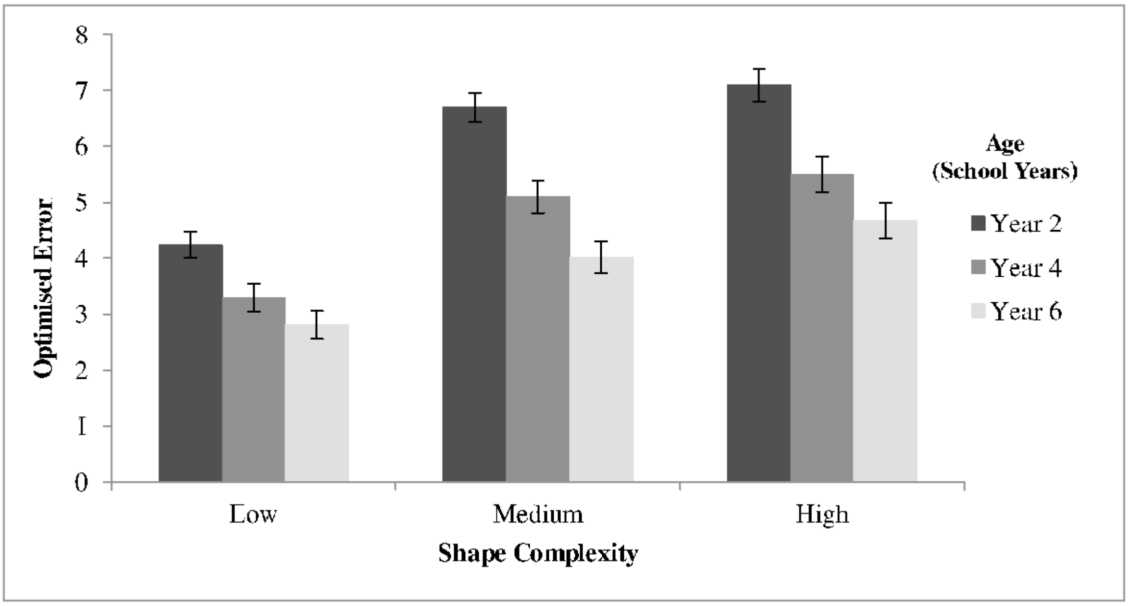

Figure 2. Bar-chart of Optimised Error (OE) by Shape Complexity and Age. Optimised Error (OE) is a quantitative measure of the accuracy with which participants' drawings replicated the target shape. Larger OE values indicate lower accuracy of replication and is treated as an index of Visual Motor Memory (VMM). Age range, within year groups, is as follows: Year 2: 6-7 years old; Year 4: 8-9; Year 6: 10-11. Statistical significant main effects for Shape Complexity and Age and no statistically significant interaction between these two factors are observed. Error bars represent 95% confidence intervals.