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Does audio-visual binding as an integrative function of working memory influence the early stages of learning to write?

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Abstract

Working memory has been proposed to account for the differential rates in progress young children make in writing. One crucial aspect of learning to write is the encoding (i.e., integration) and retrieval of the correct phoneme–grapheme pairings, known as binding. In addition to executive functions, binding is regarded as central to the concept of working memory. To test the developmental increase in binding ability and its comparative influence on writing, an experimental study assessed 5- and 6-year-olds' accuracy in retaining and retrieving bound audio-visual information alongside measures of verbal and visual complex working memory span (i.e., central executive functions), and transcription skills (i.e., alphabet and spelling). Results demonstrated an age-related increase in the ability to bind, and that binding had significant associations with working memory and early writing ability, but once binding and age were controlled for it was verbal working memory that made an independent contribution to individual differences in writing performance. Although the contribution this paper made was through an exploration and expansion of theoretical ideas within writing research, it is likely to make an important practical contribution to instruction in the future both at the level of transcription and text generation as writers develop those skills.

Keywords Working memory · Central executive · Writing transcription · Audio-visual binding · Episodic buffer

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Introduction

Linguistic, transcription and cognitive skills (e.g., phonological processes, vocabulary, receptive grammar; spelling and handwriting; working memory) provide the foundations for early writing performance (Dockrell, Ricketts, Charman, & Lindsay, 2014). Individual differences in performance in oral and written language are indirectly and directly accounted for by developmental increases in short-term memory capacity and executive functions in working memory (Adams, Bourke, & Willis, 1999; Berninger & Swanson, 1994; Berninger & Winn, 2006; Bourke & Adams, 2003; Drijbooms, Groen, & Verhoeven, 2015, 2017; Hooper et al., 2011; St Clair-Thompson & Gathercole, 2006). The precise nature of the relationships between all three factors continues to be the subject of investigation. In relation to efficiency in updating verbal and visual information in working memory, they have largely been explained in the context of trade-off accounts, whereby attentional resources are flexibly deployed to focus on information associated with the current demands of the task (Bourke, Davies, Sumner, & Green, 2014; McCutchen, 1996; Olive, 2004). For example, one of the advantages for a child with fluent vocabulary skills is that they are able to divert attention from the demands of selecting appropriate words for the text, to planning the content and purpose of the text and producing ideas in written form (Bourke & Adams, 2003). For some time now the wider concept of working memory has encompassed the importance of integration (binding) of multi-dimensional representational codes associated with information to be remembered through an episodic buffer or focus of attention (Baddeley, 2000; Cowan, 2001). Thus far, there has been limited discussion of the developmental progression of binding in young children (Alloway, Gathercole, Willis, & Adams, 2004; Gray et al., 2017), and in particular the impact this has on the development of writing. The focus of the current research was to provide a novel theoretical exploration of this issue by using an experimental protocol developed within the general area of feature integration (e.g., Treisman, 1996), to assess the contribution made by the episodic buffer and modality-specific verbal and visual central executive functions to letter and word writing skills. This is important because all of the components of working memory have a central role in learning and education (Alloway, 2009; Cowan, 2014).

Theoretical frameworks of the structure of working memory

Although there are different theories of working memory (see Adams, Nguyen, & Cowan, 2018 for review), it is generally agreed that it involves the temporary storage of a restricted amount of information to support the thoughts and actions associated with complex cognition (e.g., Baddeley, 2000; Cowan, 1999). Two dominant perspectives, Baddeley's (1986) fractionated account (i.e., phonological loop, visuo-spatial sketchpad, central executive) and Cowan's (1999) embedded processes approach, have been instrumental in determining the structure of working memory in young children and encompass the same essential features (Gray et al., 2017). Both models reflect a time-limited resource and allow for the dissociation of items based on the similarity of features (e.g., within visual and verbal domains). The central executive was characterised as a modality and storage-free resource responsible for the coordination and monitoring of information between the two storage systems (Baddeley, 1996; Cowan, 2008). It acts to control attention processes to inhibit concurrent incoming and long-term distractor information, and inappropriate responses to tasks (response inhibition), sustain attention to complete the specific goals of the task, switch attention between different sub-goals and goals to ensure efficient completion of the task (cognitive flexibility), and update information in working memory (Diamond, 2013; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000).

However, in order to explain capacity limitations, rather than dividing working memory into three factors (Baddeley, 1986), Cowan (1999; see also Engle, 2002) suggested they were determined by a unitary construct guided by the current focus of attention and susceptible to distraction and interference. Therefore, he proposed a mechanism capable of being embedded within other mechanisms. Most notably, he posited that working memory represented the currently activated portion of long-term memory that is required to support the sub-goals and goals of the cognitive task and that less attention-demanding peripheral information is relegated (Cowan, Saults, & Blume, 2014).

Furthermore, the inability of the three factor model of working memory (Baddeley, 1986) to fully account for some of the empirical findings (e.g., less than anticipated decrement in prose recall performance and chunking), led to a fourth component, the episodic buffer, being added (Baddeley, 2000). The episodic buffer therefore retrieves, integrates and maintains information relating to a set of features or properties about the same episode of experience within a limited capacity process. Up to four or five of these episodes (also known as object files; Treisman & Gelade, 1980; see Cowan, 2001, for a review of working memory capacity) can be maintained at any one time. It is this integration of multisensory (e.g., sound and shape) or unisensory features (e.g. colour and shape) into an object file that is commonly referred to as binding (Treisman, 1996). The proposal brought both models closer together since this was also the purpose of the embedded processes within a single mechanism (Cowan, 2001; Gray et al., 2017). Additionally, the central executive, which controls the content of the episodic buffer and the features that are bound, can create new binding representations from working memory, current perceptual experience, and from long-term episodic memory (Baddeley, 2000). Binding is therefore an important mechanism relevant to both learning new episodes and also in retrieving episodic information from long-term memory. Consequently, it has the potential to influence the development of education-based skills.

Development of working memory and binding

Improvements in performance on any complex cognitive task (such as reading and writing) requires not only experience, but also the maturation of the mechanisms and processes which support that task. This has practical implications in terms of how we react to this understanding within educational contexts. Gathercole, Pickering, Ambridge, and Wearing (2004) explored the structure of working memory and age-related development across the 4–15 years age range. Using tasks tapping into the phonological loop, visuo-spatial sketchpad and the central executive, they demonstrated increases in those factors from childhood through to adolescence. By the age of 6 years these basic components are in place, and they continue to improve. This is in broad agreement with other research showing improvement in working memory into adolescence, and for some functions, also into early adulthood (Huizinga, Dolan, & van der Molen, 2006).

As central executive factors control the episodic buffer and its role in integrating information, it is not surprising that research has also shown age-related change in binding performance. The development of binding across the lifespan typically shows an inverted U-shaped function (Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Brockmole & Logie, 2013). Cowan et al. (2006) showed that younger children (9 years) and older adults (65+ years) both show a decrement in their ability to bind information relative to older children and adults. This selective deficit for binding relative to memory for individual features (e.g., colour or location) was also present in older adults relative to younger adults (Chalfonte & Johnson, 1996) and when comparing children (9 and 12 years) with young adults (21 years) (Lorsbach & Reimer, 2005).

The ability to bind information is likely to support complex cognitive tasks, which in turn rely upon a capacity to store, coordinate and process information. There is limited research that has comprehensively investigated the structure of working memory in school-aged children. However, recently, Gray et al. (2017) included a wider range of assessments explicitly to test the theoretical models posited by Baddeley (1986, 2000) and Cowan (2001) in children aged 7–9 years, with regard to the best fit for the developmental data from binding and its relationship with intelligence factors. Conceptually, focus of attention rather than storage appeared to drive the relationship between working memory and intelligence in children. However, the overall conclusion was that there was potential for both models to come together to account for individual differences in the development of working memory factors (cf. Cowan et al., 2014; Hu, Allen, Baddeley, & Hitch, 2016). Beyond the scope of the current research, the question remains as to whether or not the activated portion of long-term memory (Cowan, 1999) serves the same purpose as the phonological and visuo-spatial storage components described by Baddeley (2000).

It is important to understand the mechanisms of working memory for practical as well as theoretical reasons. One of the main successes of the widely-used three-factor fractionated approach to working memory was the increased specificity with which short-term memory representations of cognition were described (e.g., Baddeley, 1986; Miyake et al., 2000). However, the importance of the contribution both this and embedded cognition perspectives can make to educational contexts is recognised (e.g., Cowan, 2014; http://calm.mrc-cbu.cam.ac.uk). Equally important was the finding that despite differences in theoretical approaches there is considerable overlap in tasks used across researchers to measure capacity limitations and/or central executive processing which have been successful in accounting for variance in children's academic performance and informed educational practice (Daneman & Carpenter, 1980; Bull & Lee, 2014; St Clair-Thompson & Gathercole, 2006; Swanson & Alloway, 2012). They include but are not limited to; measures of domain-specific short-term memory span (e.g., digit span, dot matrix; AWMA, Alloway, 2007), executive functions (i.e., inhibition [e.g., stroop, stop signal] and cognitive flexibility [e.g., object and verbal fluency]) and updating in working memory (i.e., simultaneous retention and processing of information [e.g., verbal and visual complex span tasks; AWMA, Alloway, 2007]). Therefore, the purpose of the current research was not to determine which perspective was the most valid since each theoretical component has multiple possible interpretations. The main aspect of interest was how increases in the ability to code specific components or types of information through central executive mechanisms and cross modal binding relate to higher level cognition in the form of early writing development.

Working memory, binding and emergent writing skills

Models of writing (e.g., Berninger & Winn, 2006; Berninger & Chanquoy, 2012; Kellogg, 1994; Kellogg, Whiteford, Turner, Cahill, & Mertens, 2013) have incorporated the role of working memory. Adult models (e.g., Kellogg, 1994; Kellogg et al., 2013) closely align the separable components of the original three factor model (Baddeley, 1986) to the core processes of writing (planning, text generation and reviewing). However, for children there are not only the maturational processes associated with working memory to be considered but also of the basic task of writing itself (Berninger & Chanquoy, 2012). Before linguistic units of meaning can be planned or constructed on the page and edited there needs to be a certain level of proficiency in transcription (letter writing and spelling). For emergent writers the cognitive cost of transcription is high while they are mastering transcription processes. Therefore, forming effective and efficient associations between visual and phonological codes of information will be extremely important. Researchers (e.g., Bourke & Adams, 2010; Treiman, Levin, & Kessler, 2012) have outlined the difficulties young children have with visual discrimination skills that lead to the incorrect orientation and placement of letter features when writing by hand. This idea was mirrored by research in invented spelling (e.g., Read, 1971, 1975; Zhang & Treiman, 2015) which described the degrees of mastery of the alphabetic principle as children move towards closer approximations of orthographic accuracy.

In many studies, although there were differences in the age, primary language of participants and to some extent how working memory was assessed, the results were quite similar. As children move on from basic attempts at transcription, they are able to generate words, phrases and sentences to support text generation processes (e.g., narrative coherence) (Graham & Harris, 2000; Graham, Harris, & Adkins, 2018). Research in assessing the impact of central executive functions on writing in emergent writers has predominantly found synergy with age-related performance on phonological complex span tasks (e.g., listening span) (Alloway et al., 2005; Bourke & Adams, 2003, 2010). This is not surprising, since phonological working memory and its links to phonological awareness and coding skills has successfully explained the developmental trajectory across a number of inter-related language modalities (e.g., receptive and productive language) (Adams et al., 1999; Adams & Gathercole, 2000). The findings reflect writing as a language-dependent process which includes the support of covert rehearsal processes to refresh, maintain and self-regulate attention resources to accomplish the task (Bourke & Adams, 2003; Gathercole, Alloway, Willis, & Adams, 2006). Visual working memory has also added explanatory power to models of writing both in the early childhood development literature and with adults (e.g., Bourke & Adams, 2010; Bourke et al., 2014; Kellogg, 1994; Kellogg et al., 2013; Olive & Piolat, 2002; see also St Clair-Thompson & Gathercole, 2006 for an extended investigation of executive functions and attainment tasks in English for 11–12 year old children). For young writers, a further theoretical interpretation of the relationship between verbal and visual working memory, and individual differences in writing skills is that processes requiring higher level cognitive support from underlying mechanisms are diverted to the sensory features of letters and words. The inevitable consequence is a negative impact on the efficient generation of ideas, sentences and narrative schemes required for the demands of the task reflected in education programmes (Standards & Testing Agency, 2018).

Since the primary function of binding is to maintain and integrate codes of information that are being concurrently stored and processed by working memory, this suggests that it would play an important role in writing. The dominant current position is to examine the functions of the central executive and how this relates to different ages of children, and processes, developmental stages and genres of writing (e.g., Drijbooms et al., 2015, 2017). While this is an important development and will necessarily inform instruction within the classroom, it would also be useful to begin to create an understanding of the nature and extent of the integration processes that develop in young children, especially those that relate directly to the task of early writing (e.g., audio, visual, linguistic, semantic, temporal or haptic binding). A proficient emergent writer would be a child who was able to keep in mind sufficient items and their associations to one another to be able to form legible letters of the alphabet with correct features and orientation, and from this information develop accurate spellings of words to convey ideas. Research has already shown that processing visual words leads to an early and automatic interaction with auditory brain regions whereby phonological information is extracted, presumably to support the accurate binding of audio-visual information (Wang, Wu, Liu, & Wang, 2013).

Working memory is so fundamental to writing development that it is crucial the relationship between multiple elements of the concept is determined in the early years of schooling when assessment information can lead to interventions to help support its development and prevent future problems (e.g., Berninger & Winn, 2006; Cowan, 2014; Graham & Harris, 2000). Taking on board the main tenets of two of the dominant perspectives in working memory and the influence on learning, the present study is unique because it begins to explore components of working memory using a more stringent test of the episodic buffer and binding than previously used with young children (e.g., Alloway et al., 2004 [e.g., spoken sentence recall]; see Cowan et al., 2006; Brockmole & Logie, 2013), alongside complex span tasks that have successfully measured the relationship between individual differences in writing performance and the coordination of domain-specific storage and processing of sensory information (Bourke et al., 2014; Gathercole et al., 2006; Olive & Piolat, 2002; Swanson & Alloway, 2012).

The purpose of the present study

This study had two purposes. The first was to address whether there was developmental progress in crossmodal binding ability at earlier ages than previously studied (i.e., 5 and 6 years of age) and when children begin to receive formal writing instruction in the UK. Given a lengthy set of possible types of information that need to be bound for writing we chose information relevant to the most basic units of transcription (i.e., sound and shape of letters) as these elements most represent the basis of the instruction programme the children were engaged in (Standards & Testing Agency, 2018). Once an experimental protocol is established to assess cross sensory (audio-visual) binding in children then additional information can be added to the design (e.g., spatial and temporal relationships between sound and shape; integration of long-term vocabulary knowledge). Novel stimuli were developed for both the sounds and shapes presented to the children to limit the role long-term exposure to alphabetic letters has on the relationship between the two modes of stimuli. Based on theoretical perspectives and empirical evidence outlined previously we expected there would be significant increase in age-related development of the ability to bind combinations of audio and visual material.

After ascertaining a developmental change in the ability to recall correct integrated patterns of writing-related sensory information, the second purpose was to examine the relationship between this, age of participants, central executive functions and emergent writing. We predicted there would be a significant positive relationship between binding performance, the ability to update information in verbal and visual working memory (complex span tasks), and transcription (alphabet writing and single word spelling tasks). Based on theoretical models of working memory and empirical data from the field of writing research outlined previously, a working memory model of emergent writing ability should indicate that central executive functions underpin the relationship between binding and writing. Therefore, we expected they would be independent predictors of transcription skills once binding factors had been taken into account. In particular, the model would predict a greater proportion of the variance in alphabet writing compared to spelling because of the more direct association between auditory and visual information processing.

Method

Participants

Children who met the general inclusionary criteria for typical development (i.e., did not have a developmental disability, hearing and/or visual impairment, were enrolled in Reception and Year 1 classes, with no history of ADHD, ASD and were not receiving special educational needs support) from a school in the North West of England (average socioeconomic status) were invited to participate in the study. All selected pupils spoke English as their home language. Forty-nine children were recruited from Reception Year 0 ($N=28$) ($M_{\mathrm{age}}=5$ years 1 month, $SD=3$ months, 10 male and 18 female) and Year 1 ($N=21$) ($M_{\mathrm{age}}=6$ years, $SD=3.5$ months, 7 female and 14 male). University ethical procedures were adhered to, and only those children whose parents and Head Teacher gave permission participated. Researchers collecting data were all screened by the UK Disclosure and Barring Service.

General Procedure

The participants completed the tasks administered over three sessions lasting approximately 15 min per session. The sessions consisted of the audio-visual binding experiment, working memory and writing measures. Where appropriate, the tasks were counterbalanced across the sessions.

Materials

Episodic buffer

This task was designed to assess working memory capacity when two different types of stimuli were presented across the verbal and visual domains (cross modal binding), that had to be held together in working memory to correctly respond to the task.

Audio-visual binding experiment

Stimuli for the experiment were created to fulfil a range of criteria centred on reducing the influence of prior learning and experience in order to create a purer index of binding. Visual stimuli needed to be letter-like, but not letter shapes previously encountered nor visually similar nor familiar. Similarly, sound stimuli needed to be distinct, yet retain acoustic elements resembling speech sounds.

The experiment used a change-detection design. Normally this involved memorising a set of stimuli (called the *memory display*) and then being re-presented with some or all of the original stimuli (called the *test display*) after a short memory interval. In typical change detection experiments 50% of the *test displays* involve some form of difference (called a *change* trial), whilst 50% remain the same as the stimuli in the *memory* display (called a *no-change* trial). In the current experiment 50% of trials were *change* trials. In this experiment children saw two sequential *memory* displays, each of which contained one shape and one sound. This was followed by a single *test* display that contained one shape and one sound from the previous displays, and 50% of the time an original shape-sound pairing was retained (*no-change* trial), and 50% of the time a new pairing of one sound from one display and one shape from the other display were presented (a *change* trial); this was determined on a pseudo-random basis, with one sound or shape always coming from the first memory display, and one sound or shape always coming from the second memory display. The child was then asked if the *test* shape-sound pairing is the same or different to either of the original pairings in the *memory* displays.

Visual Stimuli

Letter-like images were created by placing five black circular dots within a non-visible 3×3 matrix and jittered to create a unique pattern. In total a set of 24 images were produced, each distinct from the others. Stimuli were presented as black on a white background. For *memory display 1* the shape would appear at the top of the screen, for m*emory display 2* the shape would appear at the bottom of the screen, and for the *test display* the shape would appear at the centre of the screen.

Sound stimuli

The auditory signals consisted of 24 scrambled segments of environmental sounds extracted from the International Affective Digitized Sounds database (IADS-2; Bradley & Lang, 2007). Distinctive segments lasting 1000 ms were chosen that contained no vocalisations, and to create unrecognizable sounds each segment was scrambled in the time-domain using custom scripts in MATLAB (Mathworks). The signals were sampled at 44.1 kHz and had 30 ms onset and offset ramps to avoid audible clicks. Root mean square intensity was matched for all signals. The sounds were presented using Sennheiser HD201 headphones, with equal left–right balance, making the sound appear to come from straight ahead.

Experiment Procedure

Prior to the start of the experiment, the procedure was explained to the children in simple language and they were asked whether they understood. On the first few trials the researcher would explain the task and ensure that the child understood what was required.

An initial practice block of 12 trials was used to familiarise the child with the procedure. If the child struggled to achieve above chance performance by the end of the practice trials, then these were run again until the child understood what was required. An experiment block of 24 trials then followed. Each sound and each shape were therefore tested once in the *test display*. Due to the counterbalanced nature of the shape-sound pairings in the *memory displays*, there was no possibility to experience the same sound-shape pairings more than once, with the exception of *no-change trials*. No shape-sound pairing was tested more than once.

Each trial consisted of the following elements (see Fig. 1): A 1000 ms fixation screen followed by three 750 ms screens counting down ‘3, 2, 1’. This was followed by the first *memory* display that lasted 1000 ms. This contained one visual shape appearing centred in either the top or bottom half of the screen and was accompanied by a sound that was heard to be coming from front and centre. A blank 250 ms interval was then followed by the second *memory* display that contained a new combination of shape and sound, and the image appeared in the opposite half of the screen. After a 1000 ms blank interval a 1000 ms *test* display appeared containing

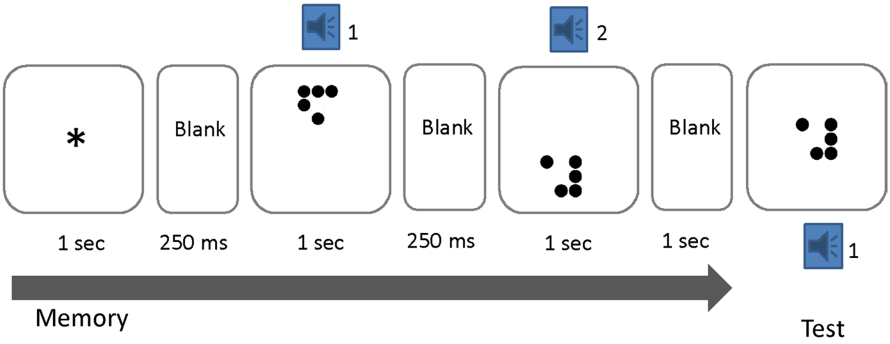

Fig. 1 An example of a *change* trial from the audio-visual binding experiment. Trial sequence moves from left to right. Child responds 'same' or 'different' depending on whether the audio-visual pairing in the *test display* is the same as an old pairing

either an old shape-sound pairing (a *no-change* trial), or a new pairing (a *change* trial). Based on the child's response, the researcher pressed the 'Z' key if the pairing was different, or the 'M' key if the pairing was the same.

Accuracy was the main dependent variable. Trials were presented in a random order to each participant, and the shape-sound pairings were also pseudo-randomly presented throughout the experiment. E-Prime 2 Professional software ran the experiment (Psychology Software Tools 2012, Pittsburgh, PA).

Central executive

The central executive tasks were taken from Automated Working Memory Assessment (AWMA) (Alloway, 2007), and are designed to assess the ability to simultaneously coordinate attentional resources in visual or verbal information in working memory. Therefore, to successfully complete the tasks children had to maintain activated memory representations while processing incoming information. The AWMA is standardised for use with children aged 4 years to adulthood (22 years).

Verbal working memory

Listening recall task (AWMA, Alloway, 2007). The participants were required to determine whether a dictated sentence was true or false (processing). At the same time they were also required to remember the final word in each sentence (updating). The participants were required to recall the final words in the correct serial order according to the set length of sentences (i.e., span length) that had been administered. The technical manual reports test–retest reliability, $r = .84$. The correlation coefficient between performance on verbal working memory and national assessment of writing at Key Stage 1 (7 year olds) (DfE, 2013) is $r = .40$. The standardised scores ranged from 70 to 108 and correspond to raw scores between 0 and 9 ($M = 2.65$, $SD = 2.75$, Skewness .80) (correlation between standard and raw scores $r = .91$).

Visuo-spatial working memory

Odd one out task (AWMA, Alloway, 2007). Participants were asked to identify the odd one out in a series of three shapes presented visually on a computer screen. They were then required to recall the position of the odd one out shapes in the correct serial order of presentation by tapping the positions in a matrix of boxes on the screen depending on the set size (i.e., span length). The technical manual reports test–retest reliability, $r = .87$. The correlation coefficient between performance on visual working memory and national assessment of writing at Key Stage 1 (7 year olds) (DfE, 2013) is $r = .39$. The standardised scores ranged from 67 to 105 and correspond to raw scores between 1 and 20 ($M = 6.02$, $SD = 4.06$, Skewness 1.23) (correlation between standard and raw scores $r = .93$).

Table 1 reports the mean standard scores for both age groups for the working memory assessments. Based on their M_{age} Reception children are performing less well than anticipated on visual and verbal complex span tasks (M standard score < 85) and those in Year 1 indicate an average performance (M standard score in 85–115 range). To maintain consistency with the inclusion of non standardised scores for performance on the binding experiment for which the measurement of age-related developmental changes were critical, the raw scores were reported in later statistical analyses.

Writing assessment

Interrater reliability was calculated by independent scoring of a randomly selected subset of 20% of the sample and calculated using intraclass correlations (ICC) based on absolute agreement between the two raters.

Alphabet

In this task, children were required to write the upper- and lower-case forms of all letters in the alphabet (Ritchey, 2008). The letters were presented orally in a fixed

Table 1 Descriptive statistics for executive functions and emergent writing measures by year group

Group	Executive function		Emergent writing	
	Visual WM	Verbal WM	Alphabet	Spelling
Mean				
Year 0	78.82	82.46	20.24	4.64
Year 1	90.38	93.24	37.38	13.95
SD				
Year 0	9.77	10.16	12.00	4.28
Year 1	13.67	15.86	7.73	8.12
Skewness				
Year 0	.74	.76	.50	1.06
Year 1	.56	− .04	− .27	.55

randomised order to all participants. The responses were scored according to their legibility. Scores ranged from 2 to 49 accurately written alphabetic letters. This method of assessing transcription is appropriate for younger children who are mastering the alphabetic principle. The range of scores was in accordance with previous research which included children of a similar M_{age} (i.e., 5 years 2 months) (Bourke et al., 2014) and slightly more varied than for children who were aged, on average, 8 months older than the current sample (Ritchey, 2008). ICC = .96, $p < .001$.

Spelling

The single word spelling task from the British Ability Scales (BAS II, Elliott, Smith, & McCulloch, 1997) required children to spell words in writing, dictated to them by the researcher. The technical manual reports test–retest reliability, $r = .64$. Concurrent validity has been assessed with the Wechsler Objective Reading Dimensions (WORD) (Psychological Corporation, 1992) Spelling Subscale, $r = .63$. Scores range from 0 to 17, with each correct spelling being awarded 1 point. The range of scores was slightly lower at the upper end compared to previous research (Bourke et al., 2014). ICC = .99, $p < .001$.

Results

Descriptive statistics for working memory and early writing skills

The descriptive statistics for working memory and writing variables are presented in Table 1. Preliminary analyses (i.e., independent samples *t* tests) revealed that there were no significant gender differences for writing (alphabet transcription, $p = .42$, spelling, $p = .14$), working memory (visual working memory, $p = .89$, verbal working memory, $p = .66$) and binding ($p = .79$). Therefore, gender was not considered in further analyses. However, there were significant differences in performance across the variables of interest according to the school year the children were in. Performance by the Reception children was lower on all measures ($p < .001$). Since children are assigned to year groups based on age, this factor was controlled for in regression analyses.

Year group analyses for the audio-visual binding experiment

The experiment analyses focused on the child's accuracy in discerning whether one of the two memory sound-shape pairings in the *memory* displays was the same or different to what was presented in the *test* display (i.e., a *no-change* or a *change* trial). Importantly, the analyses focused on both the child's sensitivity to a change occurring or not, as well as the criterion the child sets for judging whether a change has occurred or not. The criterion a child sets can affect its overall accuracy in the study, and it is therefore important that the criterions are not significantly different between age groups. For example, a child who sets a very high criterion might only occasionally respond that a change has occurred. Alternatively, if a child sets a very low criterion, then they will frequently respond that a change has occurred, leading to a high level of hits, but also a high level of false alarms (i.e., responding that a change has taken place when it has not). For this reason, using a measure of accuracy such as percent correct is not informative of overall performance.

Given that different biases in how children might choose to respond to *change* and *no-change* trials, signal detection theory (SDT) was used rather than simply a percent measure of accuracy (Green & Swets, 1966). SDT allows for a measure of sensitivity to a signal (in this case detection of change in stimuli) whilst accounting for rates of bias in a pattern of responses. Once normality tests (Shapiro–Wilks) indicated a normal distribution, two independent *t*-tests compared mean performance for *d*-Prime (sensitivity to a signal) and for *C* (bias in setting a criterion to respond to a signal) across the Year 0 and Year 1 groups.

The effect for *d*-Prime was statistically significant, $t(47) = -3.97$, $p < .001$, $d = -1.15$, $BF_{10} = 102.10$, with Year 1 being more sensitive to binding information than the Year 0 group (see Table 2 for SDT descriptives). The Bayes Factor for the *d*-Prime analysis indicated that the alternative hypothesis, sensitivity to binding information increases with age, is 102 times more likely than the null hypothesis (Jarosz & Wiley, 2014). Results indicated no significant difference in bias between the two age groups, $t(47) = -.98$, $p = .33$, $d = -.28$, $BF_{10} = .43$.

Correlation analyses for audio-visual binding, central executive, alphabet transcription and spelling

Table 3 indicates the correlation analyses for all variables. As expected there was a significant association between the age of the participants and their performance on central executive, audio-visual binding and writing measures. The older children were able to perform more efficiently and accurately across all factors. In line with previous research (Bourke & Adams, 2003, 2010; Bourke et al., 2014), both

Table 2 Descriptive statistics for signal detection theory analysis (d-Prime here is a measure of sensitivity to audio-visual binding) by year group

Group	Mean	SD	Skewness
d-Prime			
Year 0	.557	.544	.339
Year 1	1.255	.684	.121
Bias			
Year 0	–.308	.383	–.854
Year 1	–.197	.388	–.177
Hit rate			
Year 0	.702	.136	.109
Year 1	.774	.121	–.013
False alarm			
Year 0	.506	.174	.607
Year 1	.357	.192	.101

Table 3 Correlation matrix for all variables

	Measure	1	2	3	4	5	6
1	Audio-visual binding		.605***	.541***	.576***	.480***	.338*
2	Age			.741***	.506***	.637***	.579***
3	Visual working memory				.631***	.484***	.492***
4	Verbal working memory					.553***	.532***
5	Alphabet transcription						.851***
6	Single word spelling						

$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

visual and phonological working memory were significantly correlated with alphabet transcription, spelling, as well as audio-visual binding. Of principle interest to this exploratory study was the relationship between audio-visual binding accuracy (*d-Prime*) and writing development in young emergent writers. Those who could more accurately integrate audio and visual information were significantly better at writing letters to dictation and spelling single words.

Regression analyses for audio-visual binding, central executive, alphabet transcription and spelling

Regression analyses were carried out in order to investigate the extent of the relationship between the sensitivity with which children created associations between multi-representational codes and emergent transcription skills (letter and word levels). In Models 1 (criterion variable: alphabet transcription) and 2 (criterion variable: spelling), audio-visual binding accuracy was entered into Step 1. In order to assess the additional contribution to the variance made by the age of participants, visual and phonological working memory were entered into the equation in the next step. Tables 4 and 5 include the beta weights and change in R^2 values for both Models.

In Model 1, the factors accounted for 70% of the variability associated with children's letter transcription skills (adjusted $R^2 = .485$, $p < .001$). The beta weights for

Table 4 Model 1: regression analysis for audio-visual binding (d-Prime), age and executive functions with alphabet transcription ability as the criterion variable

Predictor variable	*B*	*SE B*	*β*	*t*
Step 1				
Audio-visual binding	9.150	2.464	.480	3.713***
Step 2				
Audio-visual binding	.478	2.846	.025	.168
Age	1.164	.357	.586	3.257**
Visual working memory	−.584	.592	−.179	−.987
Verbal working memory	1.727	.738	.358	2.339*

$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

Table 5 Model 2: regression analysis for audio-visual binding (d-Prime), age and executive functions with spelling ability as the criterion variable

Predictor variable	*B*	*SE B*	*β*	*t*
Step 1				
Audio-visual binding	3.744	1.522	.338	2.460*
Step 2				
Audio-visual binding	−2.053	1.721	−.185	−1.193
Age	.622	.216	.525	2.884**
Visual working memory	−.102	.358	−.054	−.284
Verbal working memory	1.141	.441	.407	2.588**

*$p < .05$; **$p < .01$; ***$p < .001$

age and verbal working memory were significant. The degree of R^2 change = .438 for the combination of factors entered into Step 2 was significant, F (4,43) = 10.144, $p < .001$. However, audio-visual binding and visual working memory failed to reach statistical significance.

For Model 2, the variables entered into the analysis accounted for 66% of the individual differences in the spelling performance between the children in the sample (adjusted R^2 = .431, $p < .001$). Therefore, Model 1 accounted for proportionally more variance in writing performance when measured by the ability to accurately and legibly produce letters of the alphabet. A similar pattern emerges when compared to letter level analyses. Age and phonological working memory again make significant independent contributions to the variance in children's emergent writing skills (R^2 change = .380, F (4,44) = 8.348, $p < .001$).

Discussion

The present study aimed to explore the role of young children's developing sensitivity to the integration of novel units of visual and sound-based information on their ability to transcribe letters and words accurately. Therefore, it extended previous research investigating the influence of visual and phonological executive functions on the developmental progression of writing skills (Bourke & Adams, 2003, 2010; Bourke et al., 2014). In order to accomplish this, a new experiment was developed incorporating novel audio and visual stimuli. In a younger age group than previously studied, the results from the experiment support age-related changes in binding ability and therefore, the structure of working memory in children. Furthermore, that a higher degree of sensitivity to changes in associations between audio and visual information was significantly related to visual and verbal executive functions and transcription skills. Although binding was not able to predict writing outcomes at this stage of development once age and complex memory span had been taken into account, this was not entirely unexpected since it is still unknown how this element of working memory interacts with the cognitive processes underpinning literacy, and also the age at which the ability to bind has matured sufficiently to make a significant contribution.

The experiment set out to determine whether audio-visual binding (specifically, as this is fundamentally important to reading and writing) developed between the first and second years of formal education in the UK. The stimuli were designed to prevent prior experience of audio-visual pairings, and therefore long-term memory, from influencing the results. Using such stimuli also allows the results to be generalised more widely to different populations. To the authors' knowledge, this is the first time that children at such an early age have been tested on their ability to bind audio-visual information using novel stimuli as a measure of the constraints associated with the episodic buffer (e.g., Alloway et al., 2004; Cowan, 2016; Gray et al., 2017). The results clearly demonstrate a developmental progression between the ages of 5 and 6 years. This is consistent with Gathercole et al.'s (2006) findings that most working memory functions appear to be in place by 6 years of age; though they did not test the episodic buffer or binding. It is also consistent with more general developmental trends in binding showing an increase throughout later childhood/early adulthood, and a decline in older adults (Brockmole & Logie, 2013). Most importantly, the decision criteria employed by the children to enable them to respond to the task did not differ between the two age groups. Given that the sensitivity to the signal did develop, one can assume that without prior experience of the stimuli, the experiment has demonstrated a binding effect that undergoes a process of maturation, alongside learning to make such associations. Although steps were taken to preclude the influence of prior learning, the effect of conceptual knowledge about the purpose for making sound-shape (i.e., phoneme–grapheme) associations will, most likely, also make a contribution to enhancing strategy development that increases processing speed and capacity limitations which impact on performance (Cowan, 2014).

Nonetheless, a main finding from the current research was the significant link between phonological central executive updating functions and writing. Since this is previously documented, especially as children begin to master transcription skills and move towards the development of narrative writing and other genres, it is not an entirely novel finding (Alloway et al., 2005; Bourke & Adams, 2003; Swanson & Berninger, 1994). Interestingly, given the unique contribution of visual working memory to the compositional quality of narratives by young children in previous research (Bourke & Adams, 2010; Bourke et al., 2014) and the close links between text quality and transcription skills (Graham & Harris, 2000; Limpo & Alves, 2017; McCutchen, 1996), this factor was not a significant predictor of transcription skills in this study. It seems, therefore, that transcription skills predominantly require support from a resource that will maintain and update sound-based (and/or language-related) information in working memory. Therefore, in order to minimise errors (e.g., inversion, reversal, transposition of individual features comprising letters) the retention of phonological information requires efficient and effective executive processes to monitor and focus attention on the task at hand.

Furthermore, individual differences in the cognitive resources available for letter by letter processing is likely to impact on the spelling ability at this young age. The children are required to make temporal, spatial and linear associations between streams of phonological information. We know from previous research (Gentry, 1982; Pollo, Kessler, & Treiman, 2009) that children take a systematic and analytic approach to acquiring knowledge about phonology in words. Thus, suggesting that while this occurs and the processes underpinning become relatively well automatised, children will be reliant on their ability to manipulate the available capacity to simultaneously coordinate the resources required for accurate spelling.

Limitations and future research directions

Although the current study has established the role for binding audio-visual information and its relationship with age and writing, there is a question as to how this would extend to more protracted reading and writing tasks. These tasks involve not only the encoding and retrieval of sound-shape pairings, but also the temporal and spatial sequencing of such pairings to form words and sentences. Such extended tasks would involve more complex forms of binding, ones that code for the spatial and temporal relationships between phonemes and graphemes and their resultant morphemes. There are at least two distinct issues here. The first is the encoding of sequences when first experienced, for example a new series of phonemes and graphemes distributed across space and time. This learning stage will eventually lead to a retrieval stage, where it is assumed that episodic long-term memory stores the spatial and temporal binding information. This development can be viewed as the gradual automaticity of reading and writing where, one might assume, the temporal and spatial binding information becomes more easily accessible with age and experience.

Most research on binding has focused on the binding of visual information; for example, colour-shape, shape-location, colour-location (e.g. Luck & Vogel, 1997). When binding of this type is spatially or temporally separated, there is a decrement in performance due to the additional task demands (Karlsen, Allen, Baddeley, & Hitch, 2010), but such decrements are small and similar to those seen when non-separated features are remembered. In studies looking at the cross-modal binding and storage of audio-visual information that is not spatially or temporally distributed, there appears to be no cost to storing audio-visual binding compared to colour-shape (i.e., visual binding) information (Allen, Hitch, & Baddeley, 2009). It appears therefore that although coded in two separate modalities, and therefore, two separate objects of attention, that binding can treat them as belonging to the same event in the same way the visual features of a single object are treated.

Of importance for understanding reading and writing is the effect that temporal and spatial separation might have when information to be bound is from different modalities. Sound naturally has a temporal sequence when reading a word, whereas writing a word requires an understanding of the spatial arrangement of letters. Research specifically looking at the binding and retention of audio-visual information distributed across space and time appears to be very limited in scope and is an obvious candidate to develop the current experiment methodology. The stimuli used in the current experiment are also well-suited in assessing episodic short-term memory compared to episodic long-term memory, important for those first learning to read and write prior to the onset of more automated literacy skills that arise from experience and instruction. Studies already show a short-term memory benefit for words when they are presented in a sentence format versus a list format, presumably due to chunking associations between words driven by long-term representations (e.g. Baddeley, Hitch, & Allen, 2009).

The role of long-term memory for binding shapes and sounds can also be determined by comparing systems of instruction in different countries where the age of formal tuition differs. This would be important for understanding the impact of learning specific grapheme-phoneme associations, and also the influence of being taught to make associations more generally. If the ability to bind develops through normal maturation processes, one would expect the ability to bind novel stimuli to be the same across institutions where formal tuition begins at different ages. Conversely, if being taught to make such arbitrary associations as those between a set of graphemes and phonemes bestows a binding benefit, one would expect that children formally taught literacy skills at an early age would have an advantage. Of course, given the limited scope of current studies, and the limited age range that has been studied, it would also be worthwhile to establish a more fine-grained understanding of how binding develops and its relationship with literacy skills.

The process of reading and writing also includes understanding the actions required to execute both the eye movements required to read, as well as the haptic actions necessary to write. A full model of executive functioning and binding and its role in supporting reading and writing would therefore include how audio-visual information is bound to action planning and execution. One such model for cognition more generally, is Hommel's Theory of Event Coding that integrates perception (e.g. audio-visual binding) and action (e.g., haptic routines and sequences) in the form of what he calls Event Files (Hommel, Musseler, Aschersleben, & Prinz, 2001). A more holistic understanding of the process of writing might therefore benefit from studies that explore the relationship between audio, visual and haptic features of a written task.

Finally, the study was limited by the lack of inclusion of strong control (e.g., nonverbal cognitive ability and/or verbal reasoning) and linguistic variables, and was based on a restricted sample. Although, the contribution made by verbal central executive factors to early writing development has been reliably demonstrated across studies once those factors have been taken into account (Alloway et al., 2005; Bourke & Adams, 2003; Kim, Al Otaiba, Wanzenk, & Gatlin, 2015; Swanson & Berninger, 1994), they are likely to mediate the quality and productivity of writing, especially for emergent writers (Dockrell et al., 2014). A further omission was a fuller exposition of the processes involved in the maintenance of representations (e.g., domain-specific storage) and executive functions (e.g., response inhibition and cognitive flexibility) (Baddeley, 1986; Miyake et al., 2000) which either individually or interactively could contribute to the development of text-based writing skills as children mature and gain experience in associated literacy based tasks (Drijbooms et al., 2015, 2017). Inclusion of short-term capacity measures of working memory (e.g., digit span) could have provided a clearer indication of whether the poor performance by some children on the verbal working memory task was accounted for primarily by a capacity limitation, or by an immature executive function. It would also allow for a more nuanced estimation of whether intact functioning of the storage component of verbal working memory could support the fact that there were no age-related floor effects on any of the other measures in the study.

Educational implications

Learning occurs when a new concept is developed when existing ideas are joined and bound together. It follows that understanding of letters will lead to links with words and related properties including goals related to communication. The focus of attention required to build rich networks of associations can be assisted by training and a sensitive alignment between the teaching of children in accordance with individual working memory constraints (Cowan, 2014; Harris et al., 2012). One important related strategy is chunking (i.e., formation of new associations or recognition of existing ones) of information which leads to a reduction in the number of independent items/features that need to be monitored by the child. An individualised plan to support integrative learning and reduce cognitive load can be facilitated by computerised technology. Another approach would be to consider delaying the formal teaching of phoneme–grapheme associations to spell words until children gained familiarity with the concept of writing which could be through enhanced opportunities to read and understand ideas to develop an understanding of authorship. In order for children to learn they need to be motivated to stay on task and achieve relevant goals. If layers of complexity are built up around the act of writing from this starting point, then it is possible that younger children and those with low working memory capacity can include relatively complex and intricate representations of writing. A wider understanding of working memory and evidence associated with the concept would empower teachers to vary instructional paradigms in an imaginative and systematic way to enhance writing skills for all children.

Conclusion

The current study sought to establish a new methodology and stimuli to assess the role of the episodic buffer component of working memory in supporting early stages of writing development. Specifically, the focus was the integration of audio-visual features and how this mechanism might relate to other executive functions and simple writing tasks. The results clearly demonstrate for the first time that the ability to maintain audio-visual bindings for a short duration has a developmental trajectory, and shares variance with visual and phonological executive functions, as well as writing measures. Although for these age groups binding did not add explanatory power to the regression models, possible reasons could be that other components of executive functioning need to develop sufficiently for the role of binding to emerge as a significant predictor. Future studies should focus on additional and more complex forms of binding that relate to sustained reading and writing tasks (e.g. spatial and temporal audio-visual binding), include robust control variables and measurements of linguistic skills, as well as extending the age range beyond the very earliest stages of formal writing instruction.

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