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Evaluating the developmental trajectory of the episodic buffer component of working memory and its relation to word recognition in children

Shinmin Wang[a], Richard J. Allen[b], Jun Ren Lee[a] and Chia-En Hsieh[a]

[a]National Taiwan Normal University, Taipei, 10610, Taiwan

[b]University of Leeds, Leeds, LS2 9JT, UK

Correspondence concerning this article should be addressed to Dr. Richard Allen, Institute of Psychological Sciences, University of Leeds, Leeds, LS2 9JT, UK. Telephone: +44(0)113 343 2667. Email:R.Allen@leeds.ac.uk , and Dr. Jun Ren Lee, Department of Educational Psychology and Counseling, National Taiwan Normal University, No. 162, Sec. 1, Heping E. Rd., Da-an District, Taipei 10610, Taiwan. Telephone: +886(2)7734 3787. Email: jrlee@ntnu.edu.tw .

Abstract

The creation of temporary bound representation of information from different sources is one of the key abilities attributed to the episodic buffer component of working memory. Whereas the role of working memory in word learning has received substantial attention, very little is known about the link between the development of word recognition skills and the ability to bind information in the episodic buffer of working memory, and how it may develop with age. This study examined the performance of Grade 2 (8 yrs old) and Grade 3 (9 yrs old) children and young adults on a task designed to measure their ability to bind visual and auditory-verbal information in working memory. Children's performance on this task significantly correlated with their word recognition skills even when chronological age, memory for individual elements, and other possible reading-related factors were taken into account. In addition, clear developmental trajectories were observed, with improvements in the ability to hold temporary bound information in working memory between Grades 2 and 3, and between the children and adult groups, that were independent from memory for the individual elements. These findings suggest that the capacity to temporarily bind novel auditory-verbal information to visual form in working memory is linked to the development of word recognition in children, and improves with age.

Key words: working memory; episodic buffer; binding; reading development; Mandarin

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Working memory provides temporary maintenance of information necessary to support
complex cognitive processing. There is now considerable evidence that working memory
abilities develop through childhood (Case, Kurland, & Goldberg, 1982; 2001), with
potentially important implications for academic attainment (Gathercole & Alloway, 2008;
Gathercole, Brown, & Pickering, 2003; Jarvis & Gathercole, 2003) and more specifically, for
reading development (e.g., Swanson & Ashbaker, 2000; Swanson, Zheng, & Jerman, 2009;
Wang & Gathercole, 2013). Alloway, Gathercole, and Pickering (2006; also Bayliss, Jarrold,
Gunn, & Baddeley, 2003) found that children's performance on working memory tasks was
best captured by the Baddeley and Hitch (1974) tripartite model that sets out phonological
and visuospatial short-term stores and a central executive control resource, with each of these
components showing clear improvements from 4 years of age. Storage capacity and central
executive control are classically measured by simple and complex span tasks. While simple
span tasks require only the passive retention of information, complex span tasks involve
simultaneous storage and processing of information. As indexed by such measures, close
links between working memory capacity and development of different aspects of reading
skills have been well established, including visual word recognition (e.g., Swanson &
Ashbaker, 2000; Wang & Gathercole, 2013) and text comprehension (e.g., Cain, Oakhill, &
Bryant, 2004; Daneman & Carpenter, 1980).

More recently, Baddeley (2000) argued for a fourth component of working memory
termed the episodic buffer, that was intended to capture the binding of information from
different sources, both within and between modalities. Although this component has recently
been investigated in young adults (e.g., Allen, Hitch, & Baddeley, 2009; Baddeley, Allen, &
Hitch, 2011; Baddeley, Hitch, & Allen, 2009) and clinical populations (e.g., Allen,

Vargha-Khadem, & Baddeley, 2014; Jeneson, Mauldin, & Squire, 2010), it is less clear how the ability to effectively bind together different types of information might relate to reading development and how it develops with age. For current purposes, our specific focus is on the development of visual word recognition skills, as a factor that is closely associated with reading development. Examining this issue is of considerable value, particularly given that learning visual to phonological mappings has previously been suggested to be important in developing word recognition abilities (e.g., Hulme, Goetz, Gooch, Adams, & Snowling, 2007). The present study therefore attempts to explore how the ability to create temporary bound representation in working memory may be associated with the development of word recognition skills in children, and how this ability develops through childhood and into young adulthood.

The episodic buffer component was assumed by Baddeley (2000) to comprise a storage capacity based on a multidimensional code, which can be used to integrate information from specialized phonological and visuospatial subsystems, and to interface with long-term memory. This buffer may serve as a storage and modelling space that is informed by but separable from the specialized subsystems and long-term memory (e.g., Allen, Havelka, Falcon, Evans, & Darling, in press; Baddeley, 2012; Langerock, Vergauwe, & Barrouillet, 2014), and may form an important stage in long-term episodic learning (Baddeley, 2003). Consistent with this, children's performance on short-term feature-binding tasks intended to index the episodic buffer have been found to associate with their development of long-term episodic memory (Picard, Cousin, Guillery-Girard, Eustache, & Piolino, 2012). A range of either conjunctive or relational binding tasks that require participants to make recognition or recall judgments concerning simple combinations of features within domains (Allen, Baddeley, & Hitch, 2006; Allen, Baddeley, & Hitch, 2014), between verbal and spatial domains (Langerock et al., 2014; Morey, 2009), and across modalities (Allen et al., 2009) have been intensively used to investigate this component. Conjunctive or intrinsic binding

(e.g. of shape and color within an object) may be relatively low-level and perceptual in nature, possibly accomplished by specialized visuospatial processing before being consciously retained within the episodic buffer. In contrast, relational or extrinsic binding (Ecker, Maybery, & Zimmer, 2013; Parra et al., 2013) of elements from different domains or modalities may particularly require the episodic buffer for their formation and retention, as implied by Baddeley's original (2000) proposal. Therefore, for current purposes, episodic buffer capacity was indexed by a task in which temporary creation and maintenance of bound visual and phonological information were needed.

How might the short-term feature-binding ability attributed to the episodic buffer component of working memory possibly relate to development of word recognition skills in children? Individuals' abilities to form associations between visual and auditory-verbal stimuli in long-term memory have been repeatedly reported as a unique concurrent predictor of children's reading skills independent of their phonological processing skills such as phonological awareness and rapid automatized naming (Hulme et al., 2007; Li, Shu, McBride-Chang, Liu, & Xue, 2009; Messbauer & de Jong, 2003; Warmington & Hulme, 2012). It has been argued that this reported link reflects individuals' ability to form orthographic-phonological associations in long-term memory, and which in turn relates to reading development in children. Relatedly, evidence from imaging studies has demonstrated that a specific letter-speech sound binding deficit identified before the start of reading instruction may have contributed to later reading problems in dyslexia (Blomert, 2011). What remains to be clarified is how this initial binding ability is linked to integration of orthographic and phonological information in long-term memory. The episodic buffer component of working memory may provide a useful framework to understand this link through its proposed position at the interface between visuospatial processing, phonological processing and long-term memory, and its role in binding information from these different

sources; it therefore offers a step forward in integrating understanding of reading development with recent working memory theory.

We hypothesize that the development of word recognition is related to the ability to set up and retain associations between auditory-verbal and visual stimuli, with these being created and stored within working memory. Within the Baddeley (2000; 2012; Baddeley et al., 2011) framework, auditory-verbal and visual information would be initially processed within specialized phonological and visuospatial sub-components, with memory for associations between these elements requiring active binding within the episodic buffer. In this way, cross-modal binding as supported by the episodic buffer may be an important process in supporting formation of long-term orthographic-phonological associations, which in turn informs reading development. In line with this view, a recent study (Jones, Branigan, Parra, & Logie, 2013) compared performance of a group of adults with dyslexia and typical adults on tasks measuring working memory for binding visual and auditory-verbal information. The dyslexic group performed significantly worse than their counterparts, indicating that individual differences in creating associative information in working memory can reliably discriminate reading groups. The first aim of the current study was therefore to test this hypothesis by investigating the relationship between children's word recognition and their performance on a working memory binding task where formations of temporary bound representation of visual and auditory-verbal information were required. We predicted that this measure of proposed episodic buffer function would be associated with the development of word recognition skills, above and beyond any contribution of specialized visuospatial and phonological working memory subcomponents (as measured by simple tests of feature memory)

A second question of interest concerns how binding processes in the working memory component of episodic buffer might develop through childhood. A number of studies have applied various tasks aimed at measuring working memory for features and their bindings to

children of different ages. In a large-scale online study of visual memory, Brockmole and Logie (2013) found that binding between colour and shape showed a developmental trajectory from 8 years old and into adolescence, with younger children recalling a higher rate of unbound features. Other studies have administered tasks tapping binding between features and locations, and generally found developmental improvements from younger to older children, and into adulthood (e.g., Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Lorsbach & Reimer, 2005; Picard et al., 2012). In the purely verbal domain, Alloway, Gathercole, Willis, and Adams (2004) examined binding using sentence recall alongside a range of other measures, and found evidence for developmental improvements from 4 years of age. Development of cross-domain associations (i.e. between verbal and spatial information) is also apparent. For example, Cowan, Saults, and Morey (2006) found that memory for binding between visually presented names and locations improved between third grade (9-10 years), sixth grade (12-13 years) and adult participants, and also predicted performance on working memory span tasks. Taking a different approach, Darling et al. (Darling, Parker, Goodall, Havelka, & Allen, 2014) observed that 6-year olds did not benefit from binding verbal-spatial information in working memory in digit recall, while 9-year olds and young adults did, suggesting a developmental shift in the ability to associate and utilize information from across domains.

Overall then, previous work on binding in children has indicated changes through childhood and when compared to young adults, though these improvements are not always clearly differentiated from memory for the individual features. In particular, the general focus on binding within or between domains may not capture the potential multi-modal nature of the episodic buffer as originally set out by Baddeley (2000). In fact, no previous studies to our knowledge have examined development of working memory for binding between auditory-verbal and visual information in children. This form of associative processing may

be a relatively strong test of episodic buffer functioning, and furthermore may show a particular developmental trajectory that can be differentiated from memory for individual elements. While we would expect memory for constituent visual or verbal information to improve through childhood (e.g., Gathercole, Pickering, Ambridge, & Wearing, 2004), relatively little is known about how memory for the associations between these elements might also improve; identifying a separable developmental trajectory for this binding processing would provide novel support for the notion that this draws on particular cognitive resources, rather than simply drawing on memory for the constituent elements. Therefore, the second aim of the present study was to explore the ability of children and young adults to bind arbitrary pairings of visual and auditory-verbal information in working memory.

In sum, the aim of the current study was two-fold. First, we investigated whether the ability to create temporary bound representation of visual and auditory-verbal material in working memory associates with the development of word recognition skills in children when contributions of feature memory and other relevant factors (e.g., phonological awareness and rapid automatized naming) were taken into account. Second, we explored the developmental trajectory across school children and young adult groups on the task measuring working memory for visual and auditory-verbal information binding. We examined accuracy and error patterns that were produced in the working memory binding task (e.g., Ueno, Mate, Allen, Hitch, & Baddeley, 2011), in order to help specify the nature of developmental improvements.

An adapted reconstruction task was used to measure working memory for visual and auditory-verbal material binding. This task paradigm has been successfully used to investigate the ability to create temporary bound representations in working memory in clinical patients (Allen, Vargha-Khadem, et al., 2014; Jeneson et al., 2010). Comparable performance patterns have been found between reconstruction tasks and the widely-used

single probe recognition tasks (Allen, Vargha-Khadem, et al., 2014). Reconstruction tasks were chosen over single probe recognition tasks in the current study because the former potentially provide a measure of memory for every item in each of the sequence (Allen, Vargha-Khadem, et al., 2014). Therefore, compared to single probe tasks, reconstruction tasks can obtain sensitive data via relatively less number of trials, and as such, provide a measure that is more accessible to young children.

Method

Participants

A total of 66 children were recruited from a state primary school in Taipei County, Taiwan, including 31 second-grade children (15 boys; mean age = 99.75 months, SD = 3.39, min=96.08 months, max=103.92 months) and 35 third-grade children (20 boys; mean age = 111.47 months, SD = 3.49, min=105.20 months, max=116.24 months). None of the children has any known additional learning needs or sensory impairments. All children were native Mandarin speakers and scored no less than the 25th percentile (M = 72.58, SD = 19.60) on the Raven's Progressive Matrices (Raven, Court, & Raven, 2006). Informed parental consent was obtained and completed prior to participating. In addition, a group of 28 young adults (14 male; mean age = 255.88 months, SD = 15.36, min = 229.32 months, max = 289.58 months) were recruited from universities in Taipei, Taiwan, and paid. All of them scored no less than the 25th percentile (M = 60.30, SD = 20.49) on the Raven's Progressive Matrices, reported normal or corrected-to-normal vision and spoke Mandarin as their first language. Consent forms were obtained prior to participating.

Procedure

Children were tested in a computer room of the school across two sessions. The computerized binding task and the test of phonological awareness were administered

individually in a fixed order in the first session lasting 50-60 minutes. There was a 10-minute break between the tests. The Raven's Progressive Matrices and measure of word recognition were given to the whole class followed by the rapid automatized naming ask administered individually in a second session within two weeks.

Young adults were tested individually in a university lab in two sessions within a day. Each session lasted approximately 30 min. The computerized binding task was administered in the first session, and the Raven's Progressive Matrices in the second. There was a short break between the sessions.

Measures

Working memory task for binding

Materials. All stimuli and probe items measured approximately 1.6^2cm (Allen, Hitch, Mate, & Baddeley, 2012), and were presented in black against a white background. The stimuli pool consisted of a set of 8 Mandarin auditory nonwords (*ga, bou, teng, mu, fao, hang, rei, se*) and a set of 8 abstract and non-nameable six-point shapes drawn randomly from the study of Vanderplas and Garvin (1959) (number 3, 7, 13, 19, 20, 21, 29, 30). The auditory nonwords were recorded by a male Mandarin speaker who is a qualified language therapist. All stimuli were sampled randomly without replacement within each trial and used for all participants.

Procedure. A reconstruction task used in previous research (Allen, Vargha-Khadem, et al., 2014; Jeneson et al., 2010) was adapted for the purposes of this study to measure working memory for visual and auditory-verbal information binding. In order to be able to separate participants' memory capacity for individual elements from their ability to form associations between elements in working memory, two corresponding feature memory tasks were also administered to measure memory for constituent visual and auditory-verbal elements.

Binding, visual and auditory-verbal conditions were implemented in separate blocks. To make sure that visual elements and auditory-verbal elements were equally familiar to participants in the binding condition, the binding condition was always given in the last order preceded by the visual condition and the auditory-verbal condition. The presentation order of the two individual feature memory conditions was counterbalanced across participants. There was a 3-minute break before the binding condition. Unlike adult studies where sequence lengths of 3 and 4 items were often used in the binding condition (e.g., Allen et al., 2009), the current study used list length of 2 and 3 items because we found list length of 4 item was too difficult for children to perform in our pilot study. Additionally, to equate the number of features to be remembered across conditions, list length in the feature memory conditions was set at 4 and 6 (see Jones et al., 2013for a similar design).

In the binding condition, a sequence of arbitrary pairs of visual and auditory-verbal material was presented at study (Fig. 1C). This consisted of two blocks of experimental trials for list length of 2 and 3 items. After 4 practice trials of 2-item sequences, an experimental block of 2-item sequences was administered and followed by a block of 3-item sequences. Each block contained 10 trials. Each trial began with a black fixation cross presented at the upper centre of the screen for 500 ms followed by a 250 ms blank screen delay. The to-be-remembered sequence was then presented for 2000 ms per item, with inter-stimulus intervals of 250 ms. A 1000 ms blank screen delay followed offset of the final item in the sequence, and then the test phase began.

At the test phase, either auditory nonwords (Fig. 1F) or visual shapes (Fig. 1G) were presented one at a time as retrieval cues. Simultaneously, participants saw all 8 possible choices of the other features that made up the pair in the study phase displayed at the lower half of the screen, and were required to identify the target item by mouse clicking. The maximum response time for each cue was 6s. The grey square around the items turned green

once selected and remained green till the end of the test phase as a reminder of which item had been selected. The display locations of the items at test were randomized and changed across trials to prevent the use of location cues. The auditory-verbal cue and visual cue trials were blocked and counterbalanced across participants. Cue items were selected in random order on each trial, thus nullifying the possible role of serial order mechanisms. Dependent variable was proportion of correct responses averaged across sequence lengths

On the trials where visual shapes were presented as retrieval cues, auditory nonwords were displayed as response options in their visual forms--Zhu Yin Fu Hao (Fig. 1G) -- a phonetic symbol system designed to represent the sounds of Chinese characters in Taiwan. Recent evidence indicates that spoken response may have strongly mediated the relationship observed between reading skills and relevant cognitive predictors (Litt, de Jong, van Bergen, & Nation, 2013; Wang & Gathercole, 2014). This design allows a manual response and therefore potentially rules out the possibility that requirement for spoken response might drive any link observed. These symbols are regularly used in textbooks to help children to access pronunciations of characters and are highly practiced for the second graders as well as older children. No participants were reported to have problems recognizing these symbols with ease. Moreover, possible contributions of symbol recognition skills to outcomes related to binding performances may be ruled out by statistically controlling for performance on a corresponding auditory-verbal feature memory task as described below.

In the corresponding memory task measuring the constituent auditory-verbal features (Fig. 1A), a sequence of 4 or 6 auditory nonwords was presented via a headphone with a white screen as background. After 4 practice trials of 2-item sequences, an experimental block of 4-item sequences was administered, followed by a block of 6-item sequences. The task procedure at study was identical to that employed in the binding condition, except that the presentation time for each element was now set at 1000ms so that processing time for

features was equivalent across the binding and feature memory conditions (see Jones et al., 2013, for a similar design). At test, corresponding to the design in the binding condition, all 8 possible nonwords were displayed in their visual forms at the lower half of the screen (Fig. 1D), with participants using the mouse to select the target items in any order. No serial order element was required as this is not an explicit part of the binding task. The next trial started automatically once all responses had been made or when the total response time exceeded 24s for block 1 (4-item sequence) and 36s for block 2 (6-item sequence). This gave 6s on average for each response. The dependent variable was proportion of correct responses averaged across sequence lengths. For the visual condition (Fig. 1B and 1E), the procedure was identical to that employed in the auditory-verbal condition, except that the experimental stimuli were replaced by a set of 8 shapes described above and presented sequentially at the upper centre of the screen at study.

INSERT FIGURE 1 ABOUT HERE

Reading-related measures

Phonological awareness. The Oddity Task (Lee, 2009) was used to assess children's awareness of the phonological structure of words. In this task, children had to indicate the odd word in a series of 3 auditorily presented words, where 2 words had a common initial or final sound (e.g., fen2, su2, fei2 / rang4, pei4, nei4). The words for each oddity trial were recorded by a native female Mandarin speaker and were presented to the child through headphones. The child heard each trial two times and was required to identify the odd word. The experimenter recorded the child's answer in a sheet and then pressed the spacebar to continue. The child was allowed to correct their response before the next trial started. The test included 6 practice trials and 24 test trials. Feedback was provided in the practice trials, where the experimenter let the child know whether their answers were correct or incorrect. The experimental trials consisted of 12 trials based on an initial sound change, and another 12

trials on a final sound change. These trials were intermixed and selected randomly across children. No feedback was given in the experimental trials. The total number of questions answered correctly was used as the dependent variable. Cronbach's alpha for the current study was .83 for grade 2 and .76 for grade 3.

Rapid automatized naming (RAN). The RAN number task was used in which children had to name 50 items of seven randomly repeated Arabic numbers (*0, 1, 2, 5, 6, 8, 9*) printed on 170mm x 110mm paper and laminated. The items measured approximately 10^2mm and were equally distributed in five rows in random order with 10 items in each row. The distance between the fifth and the sixth item was larger, separating the 10 items in each row into two groups. Children were asked to name the items as fast and as accurately as possible. The practice trial consisted of 27 items preceding the test phase, to ensure familiarity with the stimuli. Both accuracy and response time were recorded. The total time taken to name the whole set of numbers was used as the dependent variable.

Word recognition. Graded Chinese Character Recognition Test (Huang, 2001) was used as a standardized group administered and untimed reading measure with 200 single-syllable characters increasing in difficulty. This task is widely used in Taiwan to index children's word recognition abilities. Children were asked to write down the pronunciation of the character next to it using Zhu-Yin-Fu-Hao, with the dependent variable being the number of characters answered correctly. The raw score was transformed into a *T* score with population mean of 50 and standard deviation of 10. The test-retest reliability was .89 for grade 2 and .84 for grade 3 (Huang, 2001).

Results

Relation between binding and reading measures

Descriptive statistics for the working memory binding tasks and the reading-related

measures in children are displayed in Table 1. The children performed at a grade-appropriate

level on the standardized character recognition test. The simple (above the diagonal) and

partial (below the diagonal) correlations between measures are shown in Table 2. The simple

correlations show that the measure of word recognition was significantly correlated with

phonological awareness, RAN, visual memory and importantly, with binding memory.

Phonological awareness, RAN and binding memory were also significantly related to one

another. The overall patterns remain similar after chronological age was controlled, although

the correlations are slightly lower than the simple correlations and visual memory no longer

correlates with word recognition.

INSERT TABLE 1 AND TABLE 2 ABOUT HERE

A set of hierarchical regression analyses were carried out with children's word

recognition skills as a dependent measure (Table 3). In each analysis, chronological age was

entered at Step 1 and auditory memory and visual memory at Step 2, to control age effects

and feature memory performance. Regression 1 revealed that binding memory was a

significant predictor of word recognition above and beyond feature memory, and accounted

for unique 5.2% of variance in word recognition. The second set of regression analysis

further indicated that binding memory remained a unique predictor of word recognition

(accounting for 4.2% of variance) when variances due to phonological awareness and RAN

were also controlled. Together all variables explained 47.0% of the variance in word

recognition. Thus, children's ability to bind visual and auditory-verbal information in

working memory was a unique predictor of word recognition after controlling for age, feature

memory, phonological awareness, and rapid naming ability.

INSERT TABLE 3 ABOUT HERE

Given that the binding task is more demanding and therefore more likely to rely on

general cognitive ability relative to the single feature tasks alone, an additional regression

was performed with age and nonverbal ability (measured by Raven's Progressive Matrices) entered at Step 1 and auditory and visual memory at Step 2. Binding memory remained a significant predictor at Step 3 (accounting for 4.0% of variance), suggesting that the link between the working memory binding task and word recognition did not simply reflect effects of general cognitive resources (Table 3).

Age differences in working memory binding

The proportion of the total number of items that were correctly selected in each condition of the binding task was displayed in Figure 2. A 3x3 mixed-design ANOVA was conducted with age group (Grade2, Grade3, young adults) as a between-subject factor and memory condition (visual, auditory-verbal, binding) as a within-subject factor. All effects were reported as significant at $p < .05$. The results showed significant main effects of age group, $F(2, 90) = 72.63$, $MSE = .005$, $\eta_p^2 = .62$, $p < .001$, and memory condition, $F(2, 180) = 316.14$, $MSE = .006$, $\eta_p^2 = .78$, $p < .001$, and a significant interaction between group and memory condition, $F(4, 180) = 25.53$, $MSE = .006$, $\eta_p^2 = .36$, $p < .001$. Simple effects analyses indicated that there was an effect of age group in the visual condition, $F(2, 90) = 36.76$, $MSE = .005$, $\eta_p^2 = .45$, $p < .001$. Further comparisons (adjusted using Bonferroni-Holm) revealed young adults ($M = .86$, $SD = .07$) remembered more items than Grade 2 ($M = .73$, $SD = .07$) and Grade 3 ($M = .72$, $SD = .07$), while the latter two groups did not differ from each other. Analysis of the age group effect in the auditory-verbal condition was also significant, $F(2, 90) = 32.91$, $MSE = .003$, $\eta_p^2 = .42$, $p < .001$. Young adults ($M = .96$, $SD = .04$) remembered more items than Grade 2 ($M = .85$, $SD = .07$) and Grade 3 ($M = .85$, $SD = .06$), while the latter two groups did not differ from each other. There was also a significant age group effect in the binding condition, $F(2, 90) = 59.79$, $MSE = .017$, $\eta_p^2 = .57$, $p < .001$, with young adults ($M = .82$, $SD = .10$) performing better than all children and Grade 3 ($M = .54$, $SD = .17$) performing better than Grade 2 ($M = .46$, $SD = .11$).

To establish whether the developmental improvements in the binding condition can be differentiated from those of memory for the constituent elements, an ANCOVA was conducted with scores on the two feature memory conditions as covariates. The age group effect for the binding condition remained significant, $F(2,88) = 10.21$, $MSE = .012$, $\eta_{p}^{2} = .19$, $p < .001$, and the pattern for group differences remained unchanged, indicating a developmental trajectory for binding that can be differentiated from memory for individual features.

INSERT FIGURE 2 ABOUT HERE

It is also informative to examine the extent to which participants made within-sequence confusion errors in the binding condition. Adapted from Ueno et al. (2011; see also Allen, Baddeley, et al., 2014), this response type involves selection of a feature that was associated with a different pairing in the presented sequence. It can be viewed as a binding error as it represents correct feature memory, but a failure to identify the appropriate pairing in which it was encountered. In order to allow for basic differences in feature memory, this error type was examined as a proportion of the total number of features correctly selected (regardless of whether they were identified in their appropriate pairings). Grade 2 children produced a mean binding error rate of .41 (SD = .12), Grade 3 a mean rate of .32 (SD = .16), and the young adult group a rate of .10 (SD= .09). A one-way ANOVA produced a significant effect of age group, $F(2,91) = 42.99$, MSE = .017, $\eta_{p}^{2} = .49$, $p < .001$. Further comparisons (adjusted using Bonferroni-Holm) revealed significant group differences between Grade 2 and Grade 3 ($p = .02$), Grade 2 and young adults ($p < .001$), and Grade 3 and young adults ($p < .001$). Thus, the probability with which a presented feature was later correctly selected but as part of an inappropriate binding decreased from Grade 2 to Grade 3 children, and Grade 3 to young adult participants.

Discussion

Children's ability to bind visual and auditory-verbal information in a working memory task appeared to be associated with their word recognition skills even when their performance on the measures of individual features and phonological processing skills were taken into account. This ability, possibly attributable to the episodic buffer component of working memory, was found to improve between second grade (8 years), third grade (9 years) and young adult participants (19-24 years), independently from memory for the individual elements. The tendency to make binding errors between features from different pairings also significantly decreased between each of the age groups. Together, these findings consistently point to a unique binding process that develops with time and is associated with children's word recognition abilities.

The relationship between children's performance on the working memory binding task and their word reading level is in line with our hypothesis, and fits with previous reports that reading groups can be readily discriminated by their working memory binding performance (Jones et al., 2013). It is worth noting that this link between working memory binding and children's word recognition skills does not appear to reflect task demands of verbal output as implied in previous research (Litt et al., 2013; Wang & Gathercole, 2014), as the use of visual forms of auditory-verbal stimuli at test meant that spoken responses were not explicitly required. It might be argued that the need to translate the auditory-verbal stimuli to their visual symbols may have contributed to the relationship observed between working memory binding task performance and reading skills. However, in the current data, the contribution of binding to word recognition remained unique after adjustment was made for performance in the auditory-verbal condition (where the visual forms of auditory-verbal stimuli were also used as response options at the test phase). This would rule out the possibilities that the link observed between working memory binding performance and word reading level in children

might have arisen from the binding task design used in the current study. We would note that it is not possible to strongly argue purely on the basis of the current study that it is specifically cross-modal binding, rather than any form of conjunctive or associative memory, that relates to the development of word recognition. Further work will be required to examine the relationship with different forms of working memory binding. Nevertheless, this study provides evidence that memory for auditory-visual binding is linked to children's word recognition abilities, even after controlling for feature memory.

How does working memory for temporary bound information from visual and auditory-verbal codes relate to word learning in Chinese children? In Mandarin, characters more clearly map onto syllables rather than phonemes. Although the use of phonological cues is possible in some cases, especially in the later stage of learning to read, the correspondences between phonological cues and character pronunciations are rather opaque (Shu, 2003). Successful word recognition is therefore inevitably reliant on the ability to form correct association between visual word forms and their corresponding pronunciations (Ho, Chan, Tsang, Lee, & Chung, 2006; Li et al., 2009), in particular for beginning readers who are less likely to optimally utilize phonological cues to assist their word acquisitions. This may have contributed to the specific role of working memory for binding between visual and auditory-verbal modalities in predicting early progress in learning to read that was observed in this study. While it remains to be seen whether this predictive relationship also emerges when examining the current tasks in the context of other languages with varying orthographic depth, we would note that the ability to associate visual with verbal information has also been shown to affect reading development in alphabetic language systems (e.g.,Blomert, 2011; Hulme et al., 2007; Jones et al., 2013). Thus, we would expect that similar results would be observed across a range of populations and languages.

Developmental trajectories in feature binding performance have previously been

observed across children and into young adulthood using a range of tasks measuring within-domain visual and spatial binding (e.g., Brockmole & Logie, 2013; Cowan, Naveh-Benjamin, et al., 2006; Picard et al., 2012), verbal binding within sentences (Alloway et al., 2004; Kapikian & Briscoe, 2012), and across-domain binding between verbal and spatial information (Cowan, Saults, et al., 2006; Darling et al., 2014). The present study extends this to a different task where visual and auditory-verbal materials were to be bound and held in working memory over short intervals. Importantly, the current study demonstrates that this developmental trend cannot be readily explained by performance improvements in the corresponding working memory tasks for individual features. Supporting evidence also comes from the observation that younger children produced a higher rate of inappropriate feature pairings in the presence of correct feature memory. Unlike tasks used in previous research, the binding between visual form and novel auditory-verbal information explored in the current study likely reflects a particular form of extrinsic or relational binding (Ecker et al., 2013; Parra et al., 2013) that relies more heavily on the active formation of new associations between modalities within a working memory storage component such as the episodic buffer (Baddeley, 2000, 2012; Baddeley et al., 2011). The current findings that these processes show a particular developmental trajectory and are separable from those shown in working memory for the constituent visual and auditory-verbal elements therefore provides novel evidence for maturation of processes associated with the episodic buffer.

In conclusion, the current study makes a unique contribution in indicating the link between word recognition in typically developing children and their ability to form and maintain temporary bound visual and auditory-verbal information, an ability closely associated with the episodic buffer component of working memory. This ability develops in general through childhood to young adulthood, and also a fine-grained level, between 8-9 years of age, and does not appear to reflect general improvements in working memory for

individual features alone, possibly indicating the maturation of processes related to the episodic buffer. Finally, it should be acknowledged that whether the ability to bind arbitrary pairs of visual and auditory-verbal information in working memory is a cause, a consequence, or a bidirectional influence on reading development is not able to be answered in the current study as all tasks were conducted concurrently. To directly address this issue, a longitudinal design will be needed in future studies.

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<div align="center">References</div>

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Table 1

Descriptive Data for Reading-Related Measures in Children

	Mean	SD	Min	Max
Word Recognition (raw, Max=200)	88.77	30.12	29	163
Word Recognition (*T* score)	65.45	11.70	40	97
Phonological Awareness (Max=24)	15.09	4.65	4	23
RAN (sec)	19.55	5.04	10	38
Auditory Memory (%)	85.12	6.39	71	99
Visual Memory (%)	72.85	6.78	59	91
Binding Memory (%)	50.19	14.84	24	93

Note. *N*=65 for RAN and Auditory Memory; *N*=66 for all the other variables.

Table 2

Correlations between Measures

Measure	1	2	3	4	5	6
1. Word Recognition (raw)	1	.35 **	-.39 **	.19	.29 *	.47 **
2. Phonological Awareness	.30 *	1	-.39 **	.56 **	.42 *	.43 **
3. RAN	-.34 **	-.37 **	1	-.31 *	-.19	-.31 *
4. Auditory Memory	.22	.56 **	-.31 *	1	.27 *	.46 **
5. Visual Memory	.22	.40 **	-.16	.27 *	1	.56 **
6. Binding Memory	.39 **	.39 **	-.26 *	.48 **	.54 **	1

Note. The correlations above the diagonal are raw and the below are partial with age group variance removed.

*p < .05. **p <.01.

Table 3

Hierarchical Regressions

	Step	Independent variables	Dependent variable				
			Word Recognition (raw)				
			final β	*p*	Total R^2	ΔR^2	*p*
Regression 1	1	Age (months)	.468	.000	.316	.316	.000
	2	Auditory Memory	.038	.732	.369	.054	.083
		Visual Memory	.015	.900			
	3	Binding Memory	.311	.023	.422	.052	.023
Regression 2	1	Age (months)	.422	.000	.316	.316	.000
	2	Auditory Memory	-.063	.617	.369	.054	.086
		Visual Memory	-.018	.883			
	3	Phonological Awareness	.115	.376	.428	.059	.059
		RAN	-.197	.072			
	4	Binding Memory	.280	.038	.470	.042	.038
Regression 3	1	Age (months)	.519	.000	.345	.345	.000
		Nonverbal Ability	.165	.125			
	2	Auditory Memory	.002	.989	.386	.042	.140
		Visual Memory	.055	.628			
	3	Binding Memory	.271	.047	.426	.040	.047
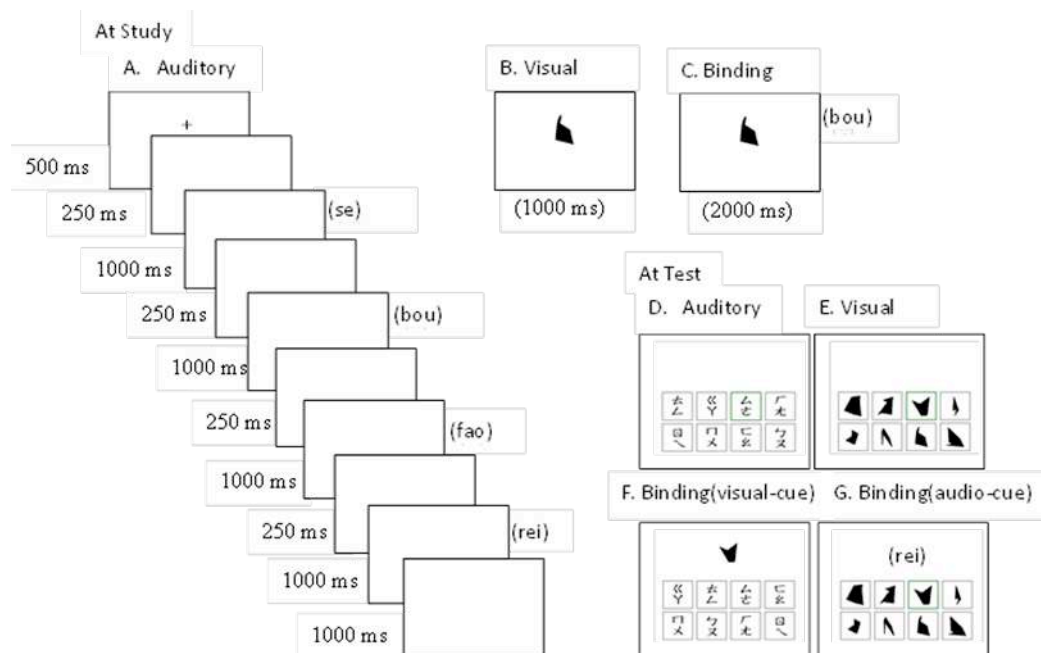
Figure1. Illustration of methodology in the working memory binding task.
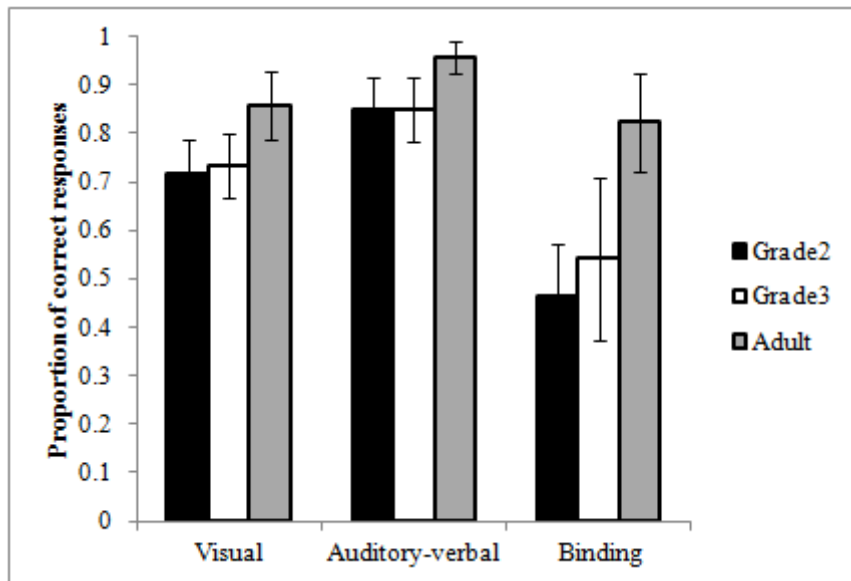
Figure 2. Mean accuracy (proportion correct) for each age group in each of the three memory conditions (with standard deviations as error bars).