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Age of acquisition effects in reading Chinese: Evidence in favour of the arbitrary mapping hypothesis

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Two experiments explored the locus of the age of acquisition (AoA) effects in the processing of Chinese characters and tested the arbitrary mapping hypothesis of AoA effects. In Experiment 1, AoA and predictability from orthography to pronunciation of Chinese characters were manipulated in a naming task. Results showed a larger AoA effect for characters from low-predictive families than for characters from high-predictive families. In Experiment 2, AoA and predictability from orthography to meaning were manipulated in a semantic category judgment task. Results showed a larger AoA effect for characters from low-predictive families than for characters from high-predictive families. In summary, the two experiments provided empirical support for the arbitrary mapping hypothesis to explain AoA effects.

In language research, age of acquisition (AoA) is an important variable that has recently drawn considerable attention as a determinant of lexical processing. A word such as 'cat', for example, is typically introduced to the vocabulary at a younger age than the word 'nun'. The word 'cat' will also be taught earlier in reading. Thus, 'cat' is considered to have an earlier AoA than 'nun'. In a number of cognitive tasks, people are faster to process early-acquired words than late-acquired words. This effect of AoA has been found in many kinds of lexical processing tasks, including lexical decision (Brysbaert, Lange, & Van Wijnendaele, 2000; Chen, Wang, Wang, & Peng, 2004; Gerhand & Barry, 1999; Ghyselinck, Lewis, & Brysbaert, 2004b; Morrison & Ellis, 1995, 2000), auditory lexical decision (Tainturier, Tamminen, & Thierry, 2005; Turner, Valentine, & Ellis, 1998), word-naming (Chen *et al.*, 2004; Gerhand & Barry, 1998; Ghyselinck *et al.*, 2004b; Gilhooly & Logie, 1981; Morrison & Ellis, 1995; Yamazaki, Ellis, Morrison, & Lambon Ralph, 1997), word-associate generation and semantic categorization

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(Brysbaert, Van Wijnendaele, & De Deyne, 2000; Chen, You, & Zhou, 2007; Van Loon-Vervoorn, 1989). In addition, AoA effects have also been found for stimuli other than words, for example, in a picture-naming task (Barry, Hirsh, Johnston, & Williams, 2001; Barry, Morrison, & Ellis, 1997; Bonin, Chalard, Meot, & Fayol, 2002; Bonin, Fayol, & Chalard, 2001; Carroll & White, 1973; Ellis & Morrison, 1998; Lambon Ralph & Ehsan, 2006; Morrison, Ellis, & Quinlan, 1992), an object decision task (Moore, Smith-Spark, & Valentine, 2004), a face categorization task (Lewis, 1999b; Moore & Valentine, 1999) and in the task requiring naming of famous faces (Moore & Valentine, 1998).

The locus of AoA effects, however, has been hotly debated. In the literature, at least two important hypotheses have been proposed: a phonological completeness hypothesis and an arbitrary mapping hypothesis. The phonological completeness hypothesis assumes that AoA effects arise at the level of phonological representation. The phonology of early-acquired words is stored wholly and completely, but as a child's vocabulary increases, the phonology is assumed to be represented in a more fragmented form. This is because the segmentation of phonological representations is more economical for their storage. However, a consequence of this efficient storage is a processing cost in which the later-acquired words are more difficult to assemble for pronunciation (Brown & Watson, 1987; Gerhand & Barry, 1998; Morrison & Ellis, 1995).

The arbitrary mapping hypothesis assumes that AoA effects reflect the arbitrary nature of the mapping between input (e.g. orthography) and output (phonological or semantic) representations formed during the development of the lexical network. Mapping between the input and output learned on one trial may or may not predict what is learned on subsequent trials (Ellis & Lambon Ralph, 2000; Monaghan & Ellis, 2002a; Zevin & Seidenberg, 2002). Specifically, when the mapping between input and output is inconsistent, or arbitrary, AoA effects will be increased. When the mapping between input and output is highly consistent, the AoA effects will be reduced. Take for instance two different rhyme units: *–ake* and *–ough*. For the word *hake* (which refers to a type of fish), its orthographic family members (e.g. *bake*, *cake*, *flake*, *lake*, *make*, *stake and take*) predominantly have pronunciations that rhyme. So, the orthographic family of *hake* is consistent in its spelling-sound correspondences (Monaghan & Ellis, 2002a). However, for the word *cough*, its orthographic family members (e.g. *bough*, *dough*, *though*, *through and thorough*) can be pronounced in several different ways. So the orthographic family of *cough* is inconsistent in its spelling-sound correspondences. According to the arbitrary mapping hypothesis, the size of the AoA effects will be influenced by the nature of the mapping between orthography and phonology, with inconsistent mappings leading to larger AoA effects.

Support for the arbitrary mapping hypothesis has been found using computational modelling. Ellis and Lambon Ralph (2000) trained a learning network to associate the orthographic and phonological patterns of words by interleaving new patterns either early or late during the training process. They found that the patterns entered early into training were better represented than the patterns entered late into training (i.e. there was an AoA effect). They suggested that the AoA effects reflect a gradual reduction in the network plasticity, because the early patterns have a chance to configure the network into a shape that is advantageous to them before the late patterns enter into training. When the late patterns are entered into training, they compete with established patterns, so they can never attain representations comparable to those of early patterns, even when trained with the same frequency. Monaghan and Ellis (2002a) extended this simulation to include consistency of mapping between input and output. They found that when the mapping between input and output was highly predictable, as it is for consistent words, AoA effects were reduced substantially. In contrast, when the mapping between the input and output was unpredictable, as it is for exception words, AoA effects were comparably much larger.

In another computational modelling study, Zevin and Seidenberg (2002) used a training corpus of monosyllabic English words with highly consistent spelling-sound correspondences. The results showed an initial advantage for the early-learned words but no residual effect of early learning on skilled performance. However, when the early- and late-learned words did not overlap in terms of orthography or phonology structure, reliable AoA effects were observed.

Lambon Ralph and Ehsan (2006) made a direct analysis of variation in mapping both in terms of connectionist simulations and data collected from English-speaking participants. They found the greatest AoA effect emerged for the arbitrary mapping, intermediate for quasi-systematic and systematic mappings, and only a very small AoA effect was found for the quasi-consistent (componential) mapping. The results were replicated in their empirical study: A substantial AoA effect was found in the picture-naming task (which involves an arbitrary mapping between semantic and phonology) but no AoA effect was observed in a word-naming task (which involved a quasi-consistent mapping between orthography and phonology).

Several empirical studies using words, pictures or faces lend support to the arbitrary mapping hypothesis. Monaghan and Ellis (2002a) found a significant interaction between word AoA and spelling-sound consistency. They found a larger difference in naming latencies between inconsistent early- and late-acquired words than between consistent early- and late-acquired words. Havelka and Tomita (2006) compared the AoA effects in naming of Japanese words written in Kanji, which involves an arbitrary mapping between orthography and phonology; and Kana characters, which involves a consistent mapping between orthography and phonology. The results showed a larger AoA effect in naming words presented in Kanji when compared with naming the same words when presented in Kana. The famous face-naming and picture-naming tasks have also provided evidence for the arbitrary mapping hypothesis. Matching a name to a face is an arbitrary process because information garnered from early-learned faces does not necessarily transfer to late-learned faces. When participants viewed faces of famous people and were required to name them, Moore and Valentine (1999) found that early-learned faces were named more quickly than late-learned faces. In a picture-naming task, which involves an arbitrary mapping between semantics and phonology, Barry *et al.* (2001) and Lambon Ralph and Ehsan (2006), both found larger AoA effects for the picture-naming task than reading aloud the printed names of the same objects.

However, other empirical studies have failed to support the claims of the arbitrary mapping hypothesis. One prediction that can be derived from the arbitrary mapping hypothesis is that AoA should be reduced when reading words in a language with transparent orthography-to-phonology mappings. Raman (2006) found AoA effects even for the highly transparent orthography of Turkish. Results showed that early-acquired words were read aloud reliably faster than late-acquired words, thus failing to support the arbitrary mapping hypothesis.

Most previous studies of AoA effects cited above have used alphabetic writing systems. In the present study, the Chinese language was used in order to explore the possible locus of AoA effects, particularly testing the arbitrary mapping hypothesis. Written Chinese is quite different from alphabetic writing systems (Perfetti & Zhang, 1995; Yan, Tian, Bai, & Rayner, 2006). The basic writing units to represent sound and meaning in Chinese are characters, which map onto a single syllable morpheme, rather than onto phonemes. Consequently, there are no spelling-sound rules as in alphabetic languages. When compared with written words in most alphabetic languages, Chinese is relatively less predictable in the mapping between orthography and phonology (Monaghan & Ellis, 2002a; Zevin & Seidenberg, 2002), thus Chinese provides an interesting tool to test the arbitrary mapping hypothesis.

Most Chinese characters (about 80–90%) are compound characters that consist of at least two subcomponents: a phonetic radical and a semantic radical (Tan & Perfetti, 1997). There are approximately 200 different semantic radicals and 1,000 different phonetic radicals (Hanley, 2005). Phonetic radicals, found mostly on the right side of a compound character, may provide information about the pronunciation of the character, including its onset, rhyme and tone. Semantic radicals, found mostly on the left side of a compound character, may convey information about the meaning of the character. For example, the character 'warship' 舰/jian4/(the number shows the tone of the pronunciation) has a phonetic radical 见/jian4/(see), which signals the pronunciation and a semantic radical 舟/zhou1/(boat), which refers to the meaning. When the exact meaning cannot be guessed from the semantic radical, it sometimes still provides more general categorical information. The information provided by the phonetic and semantic radicals, however, is not always a reliable cue to the pronunciation or meaning of the whole character (Hanley, 2005; Shu, Chen, Anderson, Wu, & Xuan, 2003). It is estimated that the phonetic radical predicts pronunciation correctly for only 39% of characters (Zhou, 1978). Moreover, for many characters, the semantic radical is not helpful in suggesting the meaning or category of the character. For instance, the character 软/ruan3/(soft) is totally unrelated to its radical found in the semantic radical location, 车/che1/(vehicle).

However, written Chinese does exhibit a different degree of predictability of the input-to-output correspondences. Characters with the same radical in the phonetic radical position can be considered as belonging to a *phonetic radical family*. Within a family, regular characters have the same pronunciation to their phonetic radical, whereas irregular characters have a different pronunciation to their phonetic radical. The ratio between regular and irregular characters within different phonetic radical families varies greatly. According to a dictionary of *Semantic and Phonetic Compound Character in Modern Chinese* (Ni, 1982), the phonetic radical 马/ma3/(horse) can be found in the following characters: 妈/ma1/(mother); 吗/ma2/(interrogative); 骂/ma4/(abuse); 码/ma3/(yard); 玛/ma3/(agate); 蚂/ma3/(ant); 犸/ma3/(a kind of ancient extinct mammal); and 杩/ma4/(traverse across the head of bed). These characters comprise a phonetic radical family in which all the characters share the pronunciations of their phonetic radical (onset and rhyme, regardless of tone). In this high-consistent family, there is a high predictability of pronunciation of family members based on the phonetic radical. In the low-consistent families, there are more irregular than regular characters and the irregular characters have different pronunciations. For instance, the phonetic radical九/jiu3/(nine) can be found in the following characters: 究/jiu1/(research), 鸠/jiu1/(turtledove), 仇/chou2/(enmity), 艽/jiao1/(a kind of plant), 犰/qiu2/(armadillo), 馗/qiu2/(force), 虓/xiao1/(roar), 尻/kao1/(buttock), 轨/gui3/(track), 宄/gui3/(wily) and 旭/xu4/(brilliance of the rising sun). As can be seen, only two family members' pronunciation (究/jiu1/, 鸠/jiu1/) are consistent with that of its phonetic radical, whereas the others are all irregular characters and most of them have different pronunciations. Therefore, in the low-consistent families, there is less predictability of members' pronunciation from the phonetic radical. Thus, in Chinese, the predictability from orthography to pronunciation is embodied by the degree to which the pronunciation of family members can be predicted by their shared phonetic radical. In high-predictive families, the pronunciation of most of its family members can be reliably predicted by the phonetic radical. In low-predictive families, the pronunciation of its family members cannot be reliably predicted by the phonetic radical.

The same characteristic applies to meaning. Words with the same semantic radical can be considered as belonging to a *semantic radical family*. The semantic radical 扌/shou3/(hand) can be found in the following characters: 打/da3/(beat); 托/tuo1/(support); 扭/niu3/(wring); 捅/tong3/(poke); 挖/wa1/(dig); 掘/jue2/(dig); 折/zhe2/(fold); 抛/pou1/(throw); 拴/shuan1/(fasten); 投/tou2/(cast); 拖/tuo2/(drag); and 拾/shi2/(pick up). The meanings of these family members all refer to actions that can be performed by hands and are thus related in meaning to their shared semantic radical. However, such consistency is not the case in all semantic radical families. Similar to phonetic radical families, the semantic radical consistency, as defined by the ratio of the number of characters whose meanings are related to their semantic radical to the number of characters in the whole family, varies greatly across families. Accordingly, the predictability from orthography to meaning in Chinese is embodied by how the relatedness of meaning among family members can be predicted by the semantic radical. In high-predictive families, readers can reliably predict that most of the family members have related meaning, but not in the low-predictive families.

Thus, a skilled reader of Chinese might be able to guess correctly the pronunciation or meaning of a newly encountered character if it is regular, just as a skilled reader of an alphabetic language can decode a new word and perhaps guess its meaning based on morphological or other cues. However, clearly some phonetic and semantic radicals are more predictive than others. Thus, the way 'regularity' and 'consistency' are defined in Chinese is somewhat different from that in alphabetic writing systems (Monaghan & Ellis, 2002a).

In the present study, we used Chinese characters to test the arbitrary mapping hypothesis of age of acquisition (AoA) effects. In Experiment 1, AoA and predictability from orthography to pronunciation were manipulated in a naming task. All regular characters were used, but some of them came from high-predictive families and others came from low-predictive families. The rationale of Experiment 1 is that the mapping from orthography to phonology of characters from a high-predictive family is more consistent than that of characters from a low-predictive family. Therefore, according to the arbitrary mapping hypothesis, larger AoA effects should be found in the naming of characters from low-predictive families compared with those from high-predictive families. In Experiment 2, AoA and predictability from orthography to meaning were manipulated in a semantic category judgment task. We predicted that larger AoA effects should be found in the characters from low-predictive meaning families compared with those from high-predictive meaning families if the arbitrary mapping hypothesis is reasonable.

EXPERIMENT 1

In this experiment, participants performed a character-naming task. We manipulated age of acquisition and phonetic family predictability.

Method

Participants

Participants were 26 undergraduate or graduate students from Beijing Normal University, from 20 to 28 years of age, all right-handed according to their reports. All of them were native Chinese speakers with normal or corrected-to-normal vision and were paid for their participation.

Design

We used a 2 (AoA: early and late) × 2 (predictability from orthography to pronunciation: high and low) within-participants design.

Materials

The stimuli comprised 56 regular characters, with 14 early-acquired and high-predictive characters (EH), 14 early-acquired and low-predictive characters (EL), 14 late-acquired and high-predictive characters (LH) and 14 late-acquired and low-predictive characters (LL). Regular characters were defined as those that have the same pronunciation as their phonetic radical, regardless of tone. The numbers of regular and irregular characters in different phonetic radical families were determined according to a dictionary of *Semantic and Phonetic Compound Characters in Modern Chinese* (Ni, 1982). If more than 70% of characters in a family were regular, then it was defined as a high-predictive phonetic family; and if more than 70% of characters in a family were irregular, then it was defined as a low-predictive phonetic family.

Age of acquisition ratings were obtained from a separate group of 30 undergraduate students at Beijing Normal University. Participants were given a booklet containing 200 characters and were asked to estimate the age at which they thought they had learned each of the characters in either spoken or written form. We used a 7-point scale, in which 1 meant acquired at 1–2 years of age, 2 meant acquired at 3–4 years of ages and 7 meant acquired at 13 years of age or older, with 2-year age bands in between.

Stimulus groups were matched for character frequency, phonetic radical frequency, and number of strokes per character, concreteness and cumulative frequency. Frequency counts of characters and phonetic radicals were based on the Dictionary of Chinese Character Information (1988). Concreteness ratings were obtained from another separate group of 30 undergraduate students at Beijing Normal University. Participants were given a booklet containing 200 characters presented in random order and were asked to rate concreteness of each item. We used a 5-point scale, in which 1 meant highly concrete and 5 meant highly abstract.

Cumulative frequency was calculated as the sum of the z scores associated with two measures of frequency. One is the adult frequency measure based on the Modern Chinese Frequency Dictionary (1986). The other is the child frequency measure, based on a corpus of Chinese textbooks from elementary school to senior high school (12 grades in all). We did this in order to avoid the potential confound of cumulative frequency in determining AoA effects (Lewis, 1999a, 1999b; Lewis, Gerhand, & Ellis, 2001). Zevin and Seidenberg (2002) argued that AoA effects in prior studies in English are likely to have been confounded with cumulative frequency, which has an impact on skilled word-naming (Zevin & Seidenberg, 2004).

Details of the character lists in each condition are shown in Table 1, and the full list of experimental stimuli is shown in Appendix A.

Table 1. Mean scores (and standard deviations) for characteristics of the stimuli used in experiment 1

Condition	AoA	CM	FC	FP	N	CON
EH	4.29 (1.13)	−0.23 (0.16)	79.21 (156.84)	440.21 (663.25)	10.21 (2.01)	2.55 (1.42)
LH	5.21 (1.23)	−0.33 (0.10)	66.22 (143.52)	427.08 (336.57)	11.71 (2.61)	2.94 (1.38)
EL	4.33 (1.18)	−0.20 (0.18)	31.75 (18.12)	598.41 (643.14)	10.31 (2.13)	2.37 (1.22)
LL	5.30 (1.24)	−0.29 (0.26)	70.90 (167.47)	471.55 (476.60)	9.64 (4.03)	3.11 (1.40)

Note. AoA, age of acquisition (in years); CM, cumulative frequency (z-scores); FC, frequency of characters (per million); FP, frequency of phonetic radical (per million); N, numbers of stroke of characters; CON, concreteness rating of characters.

Procedure

Participants were tested individually in a quiet room. The stimuli were presented on a microcomputer using E-Prime software 1.1. A typical trial in the experiment began with the presentation of a fixation cross in the centre of the screen for 500 ms. Immediately following the fixation, the target character appeared on the screen until a response was registered. Participants were instructed to name the characters as quickly as possible but to avoid making mistakes. Response latencies were recorded using a highly sensitive microphone connected to a response box. The experimenter recorded all incorrect responses or accidental microphone triggers. The order of presentation of items was randomized for each participant. Prior to the formal experiment, each participant had 10 practice trials.

Results

Naming times beyond three standard deviations of the grand mean were excluded (less than 0.5%). Mispronunciations (0.3%) and instances of accidental activation of the voice key (0.1%) were also removed from data analyses. Mean error rates in the naming task and mean naming latencies of correct responses in the four conditions are shown in Table 2.

Table 2. Mean reaction times (ms) and error rates (%) in the naming task

	High-predictability		Low-predictability	
	RT (*SD*)	ER	RT (*SD*)	ER
Early AoA	580 (60.05)	0.55	583 (59.14)	1.37
Late AoA	589 (68.32)	0.55	614 (76.50)	4.95
AoA effect	9	0.00	31	3.58

Separate two-factor ANOVAs were performed both by subjects (F_1) and by items (F_2) on the mean naming latencies of correct trials. The main effect of AoA was significant, $F_1(1, 25) = 16.25$, $MSE = 10199.52$, $p < .001$; $F_2(1, 52) = 5.93$, $MSE = 5005.74$, $p < .05$. Naming speed of early-acquired characters was faster than that of late-acquired characters. The main effect of predictability was significant, $F_1(1, 25) = 12.92$, $MSE = 5406.32$, $p < .01$; $F_2(1, 52) = 3.96$, $MSE = 3337.66$, $p = .05$. Naming speed of high-predictive characters was faster than naming of low-predictive characters. The interaction between AoA and predictability was significant by subjects, $F_1(1, 25) = 5.74$, $MSE = 2990.68$, $p < .05$, but not significant by items, $F_2(1, 52) = 2.50$, $MSE = 2105.41$, $p = .12$. Analysis of the simple main effects showed that the difference between early- and late-acquired high-predictive characters was not significant, $F_1(1, 25) = 2.18$, $MSE = 1072.10$, $p = .15$, $F_2(1, 52) = 0.37$, $p = .55$. However, the difference between early- and late-acquired low-predictive characters was significant, $F_1(1, 25) = 18.46$, $MSE = 12118.09$, $p < .001$; $F_2(1, 52) = 8.07$, $p < 0.01$, with longer reaction times for late-acquired low-predictive characters than for the early-acquired low-predictive characters.

The overall error rates were low (1.86%), and too low for legitimate parametric ANOVA. However, the pattern of the error data mirrors that of the naming time data (see Table 2).

Discussion

In Experiment 1, we found expected main effects of AoA and predictability, as well as an interaction between AoA and predictability, for the naming of Chinese characters. Naming characters from the high-predictive phonetic radical families was faster than naming characters from low-predictive phonetic radical families. Naming early-acquired characters was faster than naming late-acquired characters. The reliable effect of AoA is consistent with a previous study in which AoA and printed frequency of Chinese characters were manipulated, and AoA effects were found in spite of character frequency (Chen *et al.*, 2004). Our result is also consistent with some studies of alphabetic languages (Gerhand & Barry, 1998; Ghyselinck *et al.*, 2004b; Gilhooly & Logie, 1981; Morrison & Ellis, 1995).

More importantly, the interaction between AoA and predictability was significant. The magnitude of the AoA effect of reaction time from low-predictive phonetic radical families (31 ms) was larger than AoA effect from high-predictive phonetic radical families (9 ms). Therefore, the results of Experiment 1 provide strong supporting evidence for the arbitrary mapping hypothesis of AoA effects.

In the next experiment, we switched from phonology to semantics. AoA and predictability from orthography to meaning were manipulated in a semantic category judgment task. Again, we predicted larger AoA effects for characters from low-predictive meaning families compared with those from high-predictive meaning families.

EXPERIMENT 2

In Experiment 2, participants performed a semantic category judgment task on target characters related to animals, plants or actions. We manipulated age of acquisition and semantic family predictability.

Method

Participants

Participants were 28 undergraduate and graduate students from Beijing Normal University, from 20 to 26 years of age, all right-handed according to their reports. All of them were native Chinese speakers with normal or corrected-to-normal vision and were paid for their participation.

Design

We used a 2 (AoA: early and late) × 2 (predictability from orthography to meaning: high and low) within-participants design.

Materials

The stimuli comprised 56 characters, with 14 early-acquired and high-predictive characters (EH), 14 early-acquired and low-predictive characters (EL), 14 late-acquired and high-predictive characters (LH) and 14 late-acquired and low-predictive characters (LL).

The definition of a high-predictive meaning family was that the meanings of more than 85% of the family members were related to the meaning of their semantic radical, such as the family members with the semantic radical 扌/shou3/(hand). A low-predictive meaning family was defined as having less than 80% of the family members related to the meaning of their semantic radical. As the meaning of most Chinese characters originally had some relationship to their semantic radicals, it is hard to find enough families that meet stricter criteria for choosing low-predictive meaning families. Accordingly, 80% was chosen as the standard demarcation for being a low-predictive meaning family.

The 14 characters in each condition came from three different semantic categories: 'action,' 'animal' and 'plant.' A separate group of 30 undergraduate students rated typicality of categorical membership for these items using a 7-point scale, in which 1 meant the character does not belong to the semantic category at all and 7 meant the character fully belongs to the semantic category. The numbers from 1 to 7 represented the gradual increase of typicality. Filler items were 56 characters, in which half had the same radicals as the target stimuli and half did not. All filler items were unrelated in meaning to their semantic radicals.

Age of Acquisition and concreteness ratings were obtained from two separate groups of 30 undergraduate students at Beijing Normal University. The rating procedures were the same as described in Experiment 1. Stimulus groups were matched for character frequency, number of strokes per characters, concreteness, cumulative frequency (calculated the same as in Experiment 1) and typicality of categorical member. Details of the character lists are shown in Table 3 and the full list of experimental stimuli are given in Appendix B.

Table 3. Mean scores (and standard deviations) of characteristics of the stimuli used in experiment 2

Condition	AoA	CM	FC	N	TC	CON
EH	3.12 (1.26)	−0.21 (0.20)	41.87 (43.17)	9.85 (2.63)	6.74 (0.64)	1.77 (1.01)
LH	4.72 (1.51)	−0.35 (0.04)	30.56 (34.65)	11.14 (3.52)	6.27 (1.21)	2.12 (1.29)
EL	3.35 (1.34)	−0.21 (0.22)	79.48 (110.31)	10.79 (2.29)	6.66 (0.75)	1.75 (1.18)
LL	5.15 (1.40)	−0.37 (0.05)	46.29 (81.85)	10.14 (3.38)	6.39 (0.96)	2.28 (1.29)

Note. AoA, age of acquisition (in years); CM, cumulative frequency (z-scores); FC, frequency of characters (per million); N, numbers of stroke of characters; TC, typicality of category member; CON, concreteness rating of characters.

Procedure

Participants were tested individually in a quiet room. A trial in the experiment began with the presentation of a fixation cross at the centre of the screen for 500 ms. After the fixation, the category name (animal, plant or action) was shown for 1000 ms, followed by a blank screen for 500 ms and then the target character was presented with 2000 ms. There was a 2000 ms inter-trial interval. Participants were instructed to judge whether the character was an exemplar of the previously shown category. Participants were instructed to make responses as quickly and accurately as possible by pushing the 'yes' button with their right hand or the 'no' button with their left hand. Reaction times were measured from the onset of the target character to the onset of the participant's response. Each person received a different randomized order of trials. Before the formal experiment, each participant had 15 practice trials.

Results

Reaction times beyond three standard deviations of the grand mean were excluded (less than 1%). Mean error rates in the category judgment task and mean decision latencies of correct responses in the four conditions are shown in Table 4.

Table 4. Mean reaction times (ms) and error rates (%) in the category judgment task

	High-predictability		Low-predictability	
	RT (*SD*)	ER	RT (*SD*)	ER
Early AoA	589 (70.29)	3.57	586 (84.23)	3.85
Late AoA	614 (91.26)	7.42	651 (96.40)	7.97
AoA effect	25	3.85	65	4.12

Separate two-factor ANOVAs were performed both by subjects (F_1) and by items (F_2) on the correct categorization reaction times. The main effect of AoA was significant, $F_1(1, 27) = 36.34$, $MSE = 57236.06$, $p < .001$; $F_2(1, 52) = 12.63$, $MSE = 29635.48$, $p < .01$. Reaction times for early-acquired characters were faster than those for late-acquired characters. The main effect of predictability was significant by subjects analysis, $F_1(1, 27) = 8.60$, $MSE = 7934.15$, $p < .01$, but not by items analysis, $F_2(1, 52) = 2.05$, $MSE = 4813.49$, $p = .16$. Reaction time for high-predictive characters was faster than for low-predictive characters. The interaction between AoA and predictability was significant by subjects analysis, $F_1(1, 27) = 11.34$, $MSE = 11141.61$, $p < .05$, but not by items analysis, $F_2(1, 52) = 1.91$, $MSE = 4477.18$, $p = .17$. As there were only fourteen items in each cell of the two experiments, this might explain why the analysis by item sometimes failed to reach significance. Therefore, we focus mainly on the subject analysis. In simple main effect analyses, the difference between early- and late-acquired high-predictive characters was significant by subject analysis, $F_1(1, 27) = 7.05$, $MSE = 8934.96$, $p < .05$, but not by items analysis, $F_2(1, 52) = 2.36$, $MSE = 5537.50$, $p = .13$. The difference between early- and late-acquired low-predictive characters was significant, $F_1(1, 27) = 46.04$, $MSE = 59438.71$. $p < .01$; $F_2(1, 52) = 12.18$, $MSE = 28575.17$, $p < .01$.

Error rates in Experiment 2 were slightly higher (5.7% overall) than those in Experiment 1, but still too low for legitimate use of ANOVA. Nonetheless, the pattern is that the participants made fewer errors in early-acquired characters than in late-acquired characters (see Table 4).

Discussion

In Experiment 2, we also found expected main effects of AoA and predictability, as well as an interaction between AoA and predictability, for a semantic category judgment task in Chinese. Participants were faster to judge the meanings of characters from high-predictive meaning families than characters from low-predictive meaning families. They were also faster to judge the meanings of early-acquired characters relative to late-acquired characters.

The interaction between AoA and predictability was found to be significant in the subjects analysis. The magnitude of the AoA effect of reaction time from low-predictive meaning families (65 ms) was larger than AoA effect from high-predictive meaning families (25 ms). Therefore, the results of Experiment 2 provide further support for the arbitrary mapping hypothesis of AoA effects.

GENERAL DISCUSSION

Two experiments in Chinese provided evidence for the arbitrary mapping hypothesis. In Experiment 1, the AoA and the predictability from spelling to pronunciation in phonetic radical families was manipulated in a character-naming task. It was found that the AoA effect was larger for characters from low-predictive families (31 ms) than from high-predictive families (9 ms). These results were similar to those from Monaghan and Ellis (2002a) who found a 27 ms difference in reading aloud early- and late-acquired inconsistent words, but only a 7 ms difference for regular words. (Experiment 1 also found that there were more errors in naming early-acquired characters from low-predictive families). In Experiment 2, the AoA and the predictability from spelling to meaning in semantic radical families was manipulated in a category judgment task. Once again there was a larger AoA effect for characters from low-predictive families (65 ms) compared with characters from high-predictive families (25 ms). The results of both experiments therefore support the arbitrary mapping hypothesis, which predicts greater effects of AoA for items with more inconsistent or arbitrary mappings.

Other researchers have shown evidence in favour of the arbitrary mapping hypothesis using English stimuli (Lambon Ralph & Ehsan, 2006; Monaghan & Ellis, 2002a; Morrison & Ellis, 1995). For instance, Morrison and Ellis found that AoA effects were stronger for a lexical decision task than for naming aloud. They suggested that this might occur because semantic representations were involved in the lexical decision tasks (Millis & Button, 1989; Plaut, 1997). They asserted that the mapping between orthography and semantics was certainly arbitrary.

Furthermore, some studies directly demonstrated that the AoA effect in a word processing task was due to the activation of word meanings (Brysbaert *et al.*, 2000; Ghyselinck, Custers, & Brysbaert, 2004a; Van Loon-Vervoorn, 1989). For instance, Ghyselinck *et al.* (2004a) used the semantic Simon paradigm, in which the participants were asked to decide whether the stimulus words were printed in upper case or lower case letters and to ignore its actual semantic category. However, the participants had to respond with a verbal label, for example, half of the participants had to say 'living' in response to lower case letters and 'nonliving' in response to upper case letters. The other half received the opposite instructions. The results showed that the responses were faster in the congruent trials (e.g. saying living to 'deer' or nonliving to 'CAVE') than the incongruent trials (e.g. saying living to 'harp' or nonliving to 'FINCH'). This is because the meaning of the target word was activated automatically and interfered with the meaning of verbal response to be produced. More importantly, the congruency effect found in their study was twice as large for early-acquired words as for late-acquired words. This result indicated that the meaning was activated faster for early-acquired words than for late-acquired words. In other words, they found an AoA effect in a semantic task in which mappings from spelling to meaning are arbitrary. In the task of semantic categorization of objects, Johnston and Barry (2005) found that the objects with early-acquired names were categorized more quickly than those with later-acquired names, another obvious AoA effect.

Why does the nature of the mapping between input and output representation influence AoA effects? Computational modelling, such as that done by Monaghan and Ellis (2002a), suggested that when the early-learned patterns carry over to the late-learned patterns, the latter could exploit the network structure already established by the early patterns and so are easily assimilated. However, when the mapping between the input and output patterns is arbitrary, early-learned patterns can exert sufficient influence on the network structure to guarantee that they are well learned and represented, but late patterns have to struggle to reconfigure the network to represent them. The result is a compromise that the late-learned patterns cannot attain representation when compared with the early-learned patterns with the same frequency. Zevin and Seidenberg (2002) argued if the mapping is consistent, late-learned patterns could take advantage of network structures formed by the early learning patterns, washing out the initial advantage for early-trained words. However, if the mapping is arbitrary, the network has to memorize the individual patterns and then the AoA effects will be produced. In the present study, we provided the first evidence in Chinese language to support the arbitrary mapping hypothesis of the AoA effects, which emphasize the importance of the arbitrary nature of the mapping between input and output representations to produce the AoA effects.

The mappings of written Chinese characters to phonology and semantics are usually taught in elementary school, from Grade 1 to Grade 6, as arbitrary connections between spelling and pronunciation, and between spelling and meaning. Although the phonetic and semantic radicals can provide partial cues to sound and meaning, these cues are not always reliable. Thus, the students have to memorize the pronunciation and the meaning of individual characters during the learning process. According to computational modelling, AoA effects should be produced by this kind of learning. In fact, we did observe significant AoA effects in both our experiments. Therefore, the present study demonstrated that the age of acquisition has a relatively reliable impact on the processing of Chinese.

In both Experiment 1 and 2, we found larger AoA effects in the low-predictive phonetic and semantic radical families. This is probably owing to the fact that in the low-predictive families, people can hardly use the early-learned characters to help them learn the late-learned characters because there are so many different pronunciations and different meanings in these families. On the contrary, in the high-predictive phonetic and semantic radical families, people can learn the late-learned characters by the help of early-learned characters because the mappings are more consistent.

Other studies also shed light on the AoA effect in Chinese language (Chen *et al.*, 2004; Weekes, Chan, Kwok, Tan, & Jin, 2004). Chen *et al.* used two-character Chinese words as stimuli and found AoA effects in both a lexical decision task and a naming task. Weekes *et al*. found that early- and late-acquired Chinese words were processed by different brain regions. Early-acquired words were associated with strong activations in left superior temporal and middle frontal gyri, whereas late-acquired words were activated primarily in bilateral supramarginal gyrus and anterior cingulated cortex. In summary, these results suggest that age of acquisition plays an important role in Chinese characters recognition and processing, and that Chinese appears to be one of the languages that yield reliable AoA effects.

In our experiments, we matched our early- and late-acquired characters for their cumulative frequency. This shows that contrary to Zevin and Seidenberg's (2002) critique of some previous studies, AoA effects cannot be fully attributed to the effects of cumulative frequency. In fact, some other studies have suggested that the AoA effects were not the effect of cumulative frequency effects. For example, Ellis and Lambon Ralph (2000) found a robust and long lasting AoA effect even when the early- and late-learned patterns were presented in training an equal number of times. Morrison, Hirsh, Chappell, and Ellis (2002) used younger and older adult participants to investigate the localization of AoA effects. They reasoned that the AoA effects would be less apparent in older than younger adults in term of cumulative frequency hypothesis. However, the results showed that strong AoA effects were found for both age groups, contrary to the cumulative frequency hypothesis. In a picture-naming task, Barry, Johnston, and Wood (2006) also found that reliable AoA effects that did not differ reliably for old and young participants, again contrary to what the cumulative frequency hypothesis would predict.

Our results cannot be accounted for by the phonological completeness hypothesis. According to this hypothesis, the magnitude of AoA effects should be unrelated to the predictability from spelling to sound in Experiment 1, and that AoA effects should have less possibility to be observed in a semantic task as in Experiment 2. Our data show that this was not the case. Furthermore, Monaghan and Ellis (2002b) found no support for the phonological completeness hypothesis from their results with a phonological segmentation task. In a task of naming famous faces, Moore and Valentine (1999) also found an AoA effect, which is rather difficult to explain via the phonological completeness hypothesis. Therefore, the present experiments and some previous studies argue against the phonological completeness hypothesis.

Finally, it should be pointed out that age of acquisition might be a more complex variable than generally assumed in the literature. In the studies of Zevin and Seidenberg (2002, 2004) and Bonin, Barry, Meot, and Chalard (2004), they introduced the notion of frequency trajectory, which refers to a distribution of exposures to a word over time, to test the age-limited learning effects. Zevin and Seidenberg (2004) found frequency trajectory affected age of acquisition and it was less affected by other potentially confounding variables compared with AoA. Therefore, AoA effects may reflect the frequency at which words are encountered at different points in time. So exploring more precisely the specific sources of AoA effects will become an important issue for further studies.

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Appendix A

Early AoA high predictability	Late AoA high predictability	Early AoA low predictability	Late AoA low predictability
愉 (pleased)	膑(patella)	悠 (leisurely)	笠(a bamboo hat)
躲 (hide)	漓 (drip)	碑 (stele)	揍 (beat)
茫 (confused)	慷 (generous)	胳 (arm)	沧 (light green)
拦 (block)	询(inquire)	披 (drape over)	拘 (arrest)
捞 (gain)	擂 (pound)	盒 (box)	倦 (tired)
钩 (hook)	铭 (inscription)	趣 (interesting)	忌 (avoid)
笼 (cage)	嘻 (te-hee)	舰 (warship)	镶 (inlay)
棚 (shed)	惧 (fear)	晨 (morning)	惑 (mislead)
挺 (straight and upright)	疯 (crazy)	铺 (spread out)	炕 (kang)
挡 (keep off)	溜 (glide)	伴 (companion)	沾 (wet)
迷 (puzzle)	肌 (muscle)	抬 (carry)	胎 (fetus)
境 (border)	幔 (curtain)	炸 (bomb)	肢 (limb)
证 (certificate)	置 (set)	惊 (shock)	妄 (absurd)
梧 (phoenix tree)	控 (control)	竿 (pole)	究 (research)

Appendix B

Early AoA high predictability	Late AoA high predictability	Early AoA low predictability	Late AoA low predictability
抬 (lift)	援 (assist)	读 (read)	访 (visit)
挎 (carry)	掘 (dig)	谈 (talk)	训 (train)
摸 (touch)	扭 (wring)	订 (bind up)	诵 (recite)
捉 (catch)	迁 (move)	猩 (chimpanzee)	讥 (mock)
抢 (rob)	捻 (twist)	猪 (pig)	译 (translate)
扔 (throw)	摊 (spread out)	狗 (dog)	稞 (rye)
踢 (kick)	抛 (throw)	狼 (wolf)	秧 (seedling)
吵 (quarrel)	挠 (scratch)	狸 (fox)	秸 (straw)
唱 (sing)	鹏 (roc)	猴 (monkey)	黍 (millet)
蛙 (frog)	蜴 (lizard)	狮 (lion)	狈 (a kind of animal)
虾 (shrimp)	蜥 (cabrite)	猫 (cat)	猿 (ape)
蚊 (mosquito)	葵 (sunflower)	狐 (fox)	獐 (roe)
蛇 (snake)	苇 (reed)	稼 (crop)	鲢 (silver carp)
菜 (vegetable)	藤 (vine)	穗 (part of grass)	獭 (otter)