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The influence of age of acquisition in word reading and other tasks: A never ending story?

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Abstract

This paper concerns the influence of age of acquisition (AoA) in word reading and other tasks, and attempts to develop a number of issues raised by Zevin and Seidenberg (2002). Analyses performed on both rated and objective measures of AoA show that the frequency trajectory of words is a reliable predictor of their order of acquisition, which validates its use as a variable to examine age-limited learning effects. We report a large-scale multiple regression study of French word reading which shows that controlling for cumulative frequency (derived from child and adult frequency counts) does not result in the removal of an effect of AoA in reading aloud French words, but there was no effect of frequency trajectory. We also report some re-analyses of previous published data which show that frequency trajectory has a reliable influence on spoken and written object naming latencies and lexical decision times, but not on spelling-to-dictation or word reading latencies. Cumulative frequency has a reliable effect in all tasks. The methodological and theoretical implications of these findings are discussed.

Keywords: Age of acquisition; Cumulative frequency; Frequency trajectory; Reading; Naming; Spelling; Lexical decision

Introduction

The last decade has seen a growing number of studies investigating the effects of age of acquisition (AoA), along with those of word frequency, in a large variety of lexical processing tasks. AoA corresponds to the age at which words are first learned in either their spoken or written form (Carroll & White, 1973; Gilhooly, 1984) and AoA effects refer to the observation that words acquired early in life are processed faster and more accurately than those acquired later. AoA effects have been reported in many lexical processing tasks, including: (1) oral word reading (Bates, Burani, D'Amico, & Barca, 2001; Brown & Watson, 1987; Brysbaert, Lange, & Van Wijnendaele, 2000a; Coltheart, Laxon, & Keating, 1988; Ellis & Morrison, 1998; Gerhand & Barry, 1998, 1999a; Gilhooly & Logie, 1981; Monaghan & Ellis, 2002; Morrison & Ellis, 1995, 2000; Morrison, Hirsh, Chappell, & Ellis, 2002; Yamada, Takashima, & Yamazaki, 1998; Yamazaki, Ellis, Morrison, & Lambon Ralph, 1997); (2) visual lexical decision (Bonin, Chalard, Méot, & Fayol, 2001a; Brysbaert et al., 2000a; Brysbaert, Van Wijnendaele, & De Deyne, 2000b; Gerhand & Barry, 1999b; Morrison & Ellis, 1995, 2000; Turner, Valentine, & Ellis, 1998); (3) auditory lexical decision (Turner et al., 1998); (4) spoken picture naming (Barry, Hirsh, Johnston, & Williams, 2001; Barry, Morrison, & Ellis, 1997; Bonin, Chalard, Méot, & Fayol, 2002; Bonin, Fayol, & Chalard, 2001b; Carroll & White, 1973; Ellis & Morrison, 1998; Gilhooly & Gilhooly, 1979; Morrison, Ellis, & Quinlan, 1992; Morrison et al., 2002; Vitkovitch & Tyrrell, 1995); (5) written picture naming (Bonin et al., 2001b, 2002); (6)

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spelling to dictation (Bonin & Méot, 2002); and (7) picture naming accuracy in neuropsychological patients (Hirsh & Ellis, 1994; Hirsh & Funnell, 1995; Lambon Ralph, Graham, Ellis, & Hodges, 1998). AoA effect have also been reported in face and name processing (Moore & Valentine, 1998).

Measures of AoA correlate with word frequency and with a number of other important properties of words; words acquired earlier in life tend to occur more frequently in adulthood (as well as tending to be more concrete and shorter) than those acquired later. This has lead some researchers who have examined AoA effects to suggest, rather provocatively, that previously found word frequency effects might actually be AoA effects 'in disguise' in both word reading (e.g., Morrison & Ellis, 1995) and picture naming (e.g., Morrison et al., 1992).

Despite the abundance of reports of AoA effects, a number of methodological and theoretical issues remain unresolved. AoA effects in word reading have recently come under the critical scrutiny of Zevin and Seidenberg (2002). In an important paper for this area of research, Zevin and Seidenberg raised some major empirical concerns about previous studies of AoA in word reading in English, and also presented some very interesting theoretical explorations of AoA in terms of their connectionist model of reading. Zevin and Seidenberg's primary methodological criticism was that studies had not controlled adequately for word frequency as assessed from large and representative samples of texts taken from a broad range of reading levels (including books for children); in effect, they argued that studies of AoA had not controlled effectively for the *cumulative frequency* of the words used (i.e., how often words have been encountered throughout a lifetime of reading). Many studies of AoA effects in English matched their early and late acquired words on the frequency counts provided by Kucera and Francis (1967), but this corpus is based on a relatively small sample (of one million words) and may not provide reliable estimates across the entire range of frequencies. Zevin and Seidenberg argued that, for English, neither the Kucera and Francis nor the larger CELEX (Baayen, Piepenbrock, & van Rijn, 1993) norms provide reliable estimations of the cumulative frequency of words, as these may under-represent the frequency of word exposure in childhood. Zeno's (1995) Word Frequency Guide (WFG) is based on a large corpus (of 16 million words) drawn from broad samples of contemporary US texts and, importantly, provides estimates of how often words are encountered at multiple points, from initial acquisition (in the first grade) to adulthood. Zevin and Seidenberg argued that, in addition to the 'adult' norms (such as the CELEX corpus), the WFG should also be used to equate early and late acquired words for their cumulative frequency.

Zevin and Seidenberg (2002) carefully scrutinized the words used in the factorial investigations of AoA effects in reading aloud English words by Gerhand and Barry (1998, 1999a), Monaghan and Ellis (2002a), and Morrison and Ellis (1995), and also the lexical decision study by Turner et al. (1998). Although the early and late acquired words in these studies were matched for Kucera and Francis frequency, there were differences between the two sets of words on the frequency counts provided in the CELEX and the WFG databases, as well as differences in the ratings of lexical familiarity provided by Gilhooly and Logie (1980). In all cases, the early acquired words were both more frequent and more lexically familiar than the late acquired words, and these differences were generally statistically reliable. The only study in which they found that early and late acquired words were matched satisfactorily on WFG frequency were Monaghan and Ellis's orthographically regular words which showed no reliable AoA effect. Zevin and Seidenberg also examined AoA effects (for words where AoA ratings were available) in the results of two large-scale word naming studies, by Seidenberg and Waters (1989) and Spieler and Balota (1997), and the large-scale lexical decision study by Balota, Pilotti, and Cortese (2001), and their multiple regression analyses of these data found no effect of rated AoA. They concluded that the AoA effects reported in the studies of word reading they examined (all of which were conducted in English) are likely to have been spurious confounds with cumulative frequency (as provided by WFG). Given these methodological problems, Zevin and Seidenberg concluded that, for most English factorial studies on AoA in word reading, "the evidence for an effect of AoA on skilled reading is weak at best" (p. 2).

It is undoubtedly true that researchers need to properly control for cumulative frequency (using reliable, appropriate, and representative measures of frequency) when investigating effects of AoA and other variables related to it. It is also necessary to establish whether attempts to control for cumulative frequency would always remove effects of AoA on word reading times. This has not yet been considered, particularly for AoA effects reported in languages other than English, such as the studies of reading words in Dutch (Brysbaert et al., 2000a, 2000b), Italian (Bates et al., 2001), and Japanese Kanji (Yamazaki et al., 1997), and for lexical decision in French (Bonin et al., 2001a). The present study attempts to clarify the situation regarding the roles of AoA and word frequency in reading aloud words in French, and will also reconsider AoA (and frequency) effects in spoken and written naming, spelling to dictation, and lexical decision.

Measures of AoA and "frequency trajectory"

Measures of AoA have generally been collected by means of adult estimations of when they (or, in their opinion, children) learned particular words (e.g., Gilhooly & Logie, 1980). It is striking that such AoA ratings correlate impressively highly with more objective measures of the age at which words are actually learned (Carroll & White, 1973; De Moor, Ghyselinck, & Brysbaert, 2000; Gilhooly & Gilhooly, 1980; Jorm, 1991; Lyons, Teer, & Rubenstein, 1978; Morrison, Chappell, & Ellis, 1997; Pind, Jonsdottir, Tryggvadottir, & Jonsson, 2000), which suggests that the ratings are valid. One measure of when children have actually acquired words has been provided by Morrison et al. (1997) who asked children of various ages to name pictures. The estimation of the AoA of these object names was derived by considering when 75% of children (in any 6-month age range) could name the picture (with or without the provision of the first phoneme of the name). Chalard, Bonin, Méot, Boyer, and Fayol (2003) collected similar objective AoA norms in French, and also found that objective AoA norms are less correlated with other lexical properties (such as conceptual familiarity, word frequency, and word length) than adult ratings of AoA. Chalard et al.'s correlational results are interesting as they suggest that, when using regression analyses to predict adult naming times, their objective measure of AoA permits a better estimation of the genuine contribution of AoA over and above the other lexical variables related to it.

Objective measures of AoA must be considered to be better measures of the order of acquisition of words than ratings provided by adults, and many studies have used them to determine the influence of AoA in word processing (e.g., Ellis & Morrison, 1998). However, Zevin and Seidenberg (2002) have argued powerfully that objective AoA based on children's ability to name pictures is actually a *performance* variable. As AoA measures are difficult to estimate independently of any behavioral aspects, this leads to the problem of predicting performance in lexical tasks by AoA estimations which are also measures of performance, which Zevin and Seidenberg (2002, Ref. Note 1) refer to as the intrinsically difficult "circularity problem," which can lead AoA researchers into a theoretical morass. For example, it might be considered that it is neither surprising nor informative that items that children find difficult to name also tend to be more difficult for adults to read. Zevin and Seidenberg considered the theoretical problem of *why* some words are acquired earlier than others and introduced the notion of *frequency trajectory*. They suggested that words are learned before others because they are encountered more frequently early in life. In their modeling work, they contrasted two sets of items: (i) those that were presented frequently early but less frequently later ('early' acquired); and (ii) those that were presented rarely early but more frequently later ('late' acquired). Both sets were matched for their total or cumulative frequency. Zevin and Seidenberg found no processing advantage for the 'early' items in their model. Furthermore, Zevin and Seidenberg (2002, Ref. Note 1) also found no difference in reading latencies for words defined by frequency trajectory, although there was a clear effect of cumulative frequency.

The frequency trajectory concept is an interesting one because it allows an operationalization of age-limited learning which is not subject to the criticism of the most used measures of AoA; as a word's frequency trajectory can be estimated from child and adult frequencies, it is not a performance variable. It must be stressed that frequency trajectory as used by Zevin and Seidenberg (2002) is measured by frequencies of words in print. It is obviously the case that many words are learned early in life *before* any systematic exposure to print (and it is presumably the case that semantic constraints apply to why some words are learned before others), but the concept of frequency trajectory is certainly an important one to examine in word reading.

AoA effects in word reading in French have not been examined. In French, the BRULEX database (Content, Mousty, & Radeau, 1990) has been used to provide measures of word frequency for a range of psycholinguistic studies. However, this database has been criticized because it is somewhat outdated with the result that certain frequency estimations corresponding to words may not be reliable. The LEXIQUE database (New, Pallier, Ferrand, & Matos, 2001) is the current reference tool in French psycholinguistic research. Samples of texts written since 1950 have been extracted from a corpus of over 31 million words covering all aspects of the French language, including 16–20th century literary texts, 19–20th century scientific and technical texts, and regional variations. In addition, there is also the recent MANULEX database (Lété, Sprenger-Charolles, & Colé, in press), which uses similar methods for frequency computation as in Carroll, Davies, and Richman (1971) and Zeno's (1995) WFG. MANULEX provides frequency counts of words from a corpus of 1.9 million words in the main reading books used in French primary schools, provided for four levels: 1st grade (G1), 2nd grade (G2), 3rd to 5th grades (G3–5), and for all grades (G1–5). As LEXIQUE is mainly based on literary and technical texts, it is possible that it over-represents later-learned words, but it can be seen as a measure of 'adult' frequency. In contrast, MANULEX provides frequency estimations of words that young readers encounter ('child' frequency). The use of both the LEXIQUE and MANULEX databases allows for an estimation of the cumulative frequency of the words.

In this paper, we report a multiple regression study of French word reading latencies using both ratings and objective measures of AoA, both frequency trajectory and cumulative frequency (derived from the large and representative LEXIQUE and MANULEX databases), and a range of other relevant predictor variables, all of which tend to be correlated to various extents. We also report some re-analyses of some of our previous studies of AoA effects in spoken and written object naming, spelling to dictation and lexical decision to examine whether frequency trajectory has any reliable independent contribution in these tasks. The purpose of these re-analyses will be to examine some important theoretical claims concerning AoA effects derived from Zevin and Seidenberg's (2002) connectionist modeling work of age-limited learning effects in lexical processing tasks. However, before we address these more general issues, it is important to show that frequency trajectory does indeed have a genuine influence on the order of acquisition of words in French, as Zevin and Seidenberg (2002, Ref. Note 1) have shown in English (although they analysed only rated AoA). This is crucial for the use of frequency trajectory as an operationalization of AoA. In the following analyses, we examine this issue for both rated and objective AoA measures collected for French words.

Does frequency trajectory influence the order of acquisition of words?

In French, we have available both rated and objective AoA measures for a set of about 200 object names. Alario and Ferrand (1999) provided adult AoA ratings for the names of the Snodgrass and Vanderwart (1980) pictures. They asked 26 adults to estimate the age at which they thought they had learned each of the words in either their spoken or written form using a five-point scale (1 = learned at 0–3 years and 5 = learned at 12+ years, with 3-year age bands in between). Chalard et al. (2003) collected objective AoA norms for the same items using the procedure used by Morrison et al. (1997), namely when children were able to name the pictures. In the analyses that follow we consider several variables which may have a potential influence on adult AoA ratings and on the objective AoA norms; the variables considered were cumulative frequency, frequency trajectory, conceptual familiarity, imageability, concreteness, number of phonemes and bigram frequency. For objective AoA, name agreement, image agreement and visual complexity of the pictures were also included because, as children's picture naming was used to derive the objective AoA measure, certain characteristics of the pictures may have an influence upon them.

Cumulative frequency was calculated as the *sum* of the *z*-scores associated with the two measures of frequency (i.e., the 'adult' measure taken from LEXIQUE and the 'child' measure from MANULEX). As far as MANULEX child frequency measures are concerned, the cumulative frequency corresponding to all grades (G1–5) was used. Frequency trajectory was computed as the *difference* between the *z*-scores associated with the two measures of frequency (LEXIQUE minus MANULEX). There are two aspects worthy of note about these scores. First, we used *z*-scores and not the 'raw' (or log-transformed) frequencies because the size of the LEXIQUE and MANULEX corpora are not the same, which otherwise might have introduced some discrepancies between the two measures of word frequency. (The correlations between the *z*-scores and the log-transformed frequency scores are approximately equal to unity.) Second, the cumulative frequency and frequency trajectory scores corresponded to the two first factors of the principal component analysis performed on the two frequency measures. As a result, they are not correlated, which permit more reliable estimations of their effects.

Name agreement refers to the proportion of participants who produce the most common name; image agreement refers to the rated degree to which the mental images formed by participants in response to a picture name match the picture's appearance; and visual complexity refers to the rated level of lines and details in the drawing. Conceptual familiarity ratings (i.e., the familiarity of the concept represented by the word's referent) were taken from Alario and Ferrand (1999) and measures of imageability (i.e., the ease with which a word arouses a mental image) and concreteness (i.e., the degree to which a word's referent can be experienced by the senses) were taken from Bonin et al. (2003), who used a five-point scale for both measures (using similar methods to Paivio, Yuille, & Madigan, 1968). In order to permit comparisons between the analyses on rated and objective AoA measures, only items with a name agreement of above 75% in both the Alario and Ferrand (1999) and the Chalard et al. (2003) studies were included.

As shown in Table 1, four lexical variables made significant independent contributions to predicting the two AoA measures: conceptual familiarity, frequency trajectory, cumulative frequency and imageability. Phonological length was significant only for rated AoA. These analyses clearly show that AoA measures are indeed influenced by other lexical properties of the words. As Chalard et al. (2003) also found, rated AoA is more influenced by several lexical properties than objective AoA. (This is also reflected by the fact that the R^2 of the overall regression analysis is clearly higher for rated AoA than for objective AoA.) Hence, although the two types of norms appear to be valid indicators of the age at which a word is learned, they also appear to be composite measures. As a result, their use as independent variables to predict variations in RTs in lexical processing tasks is problematic since these tasks may also be influenced by the same variables that influence the AoA measures—the circularity problem. Importantly, frequency trajectory had a reliable contribution to both types of AoA measures, in line with what Zevin and Seidenberg (2002, Ref. Note 1) found in English

Table 1
Significant predictors of two measures of age of acquisition

	Rated AoA: $R^2 = .716$, $F(7, 171) = 61.47$				Objective AoA: $R^2 = .491$, $F(10, 168) = 16.23$			
	β	SE	t	p	β	SE	t	p
Cum Freq	−.363	.052	−6.974	.0001	−.287	.073	−3.952	.0001
Freq Traj	.339	.051	6.687	.0001	.289	.069	4.186	.0001
Fam	−.490	.053	−9.324	.0001	−.196	.080	−2.454	.015
Imag	−.191	.052	−3.695	.0001	−.365	.073	−4.990	.0001
Phons	.136	.044	3.103	.002	−.025	.060	−.423	.673

Notes. Cum Freq, cumulative frequency; Freq Traj., frequency trajectory; Fam, conceptual familiarity; Imag, imageability; Phons, number of phonemes.

regarding rated AoA.[1] Words that are encountered frequently in childhood are among those that are learned first, which is not so very surprising.

The finding of an independent contribution of frequency trajectory to both rated and objective AoA validates the use of frequency trajectory as a variable to predict latencies in word reading, naming, lexical decision and spelling to dictation. Apart from the influence of frequency trajectory, the results of these analyses suggest that certain lexical properties of the words can make them easier to learn. For instance, words that are more imageable and conceptually familiar are easier for children to name than less imageable and familiar words. This suggests that there are also semantic influences on AoA (at least for these concrete nouns). It is interesting to note that the partial R^2 between the two measures of AoA was .36 when all the other variables included in the analyses reported above were partialled out. This suggests that a common dimension, which is independent of other lexical variables and of the two aspects of word frequency, is still present in the two AoA measures.

We also performed an analysis with adult spoken object naming latencies taken from Bonin et al. (2002) introduced as predictors (plus the others described above) in order to determine whether objective AoA—a performance variable—is predicted by adult picture naming latencies, another performance variable. The outcome was straightforward: picture naming latencies account for a very large proportion of variance in objective AoA scores (the square of the semi-partial correlation was equal to .35, for a total R^2 of .67), but not in rated AoA scores. Would it be reasonable to infer that adult picture naming latencies is a 'genuine' factor that explains the order of acquisition of the words in children? Of course, anyone could claim that the same factors that affect picture naming latencies in adulthood also affect the order of acquisition of the words in children (as well as vice versa). As objective AoA is a behavioral outcome (of when children can name pictures), it is strongly related to adult picture naming times, another behavioral outcome. Therefore, it is not really surprising that objective AoA appears to be a strong reliable determinant in lexical processing tasks (and indeed the strongest predictor of adult picture naming latencies, e.g., Chalard et al., 2003). It is clear that what is required is an unambiguous objective measure of the order of acquisition of words in order to assess the influence of age-limited learning effects in word processing: frequency trajectory appears to be a very good candidate for such an enterprise.

The present experiment and re-analyses of previous published data

To our knowledge, AoA effects in French word naming have not been examined. French, like English, is an alphabetic orthography that (unlike, say, Turkish) does not have perfectly consistent spelling-to-sound correspondences, although the proportion of irregular or inconsistent words is smaller than that in English.

Our experiment adopts a multiple regression approach in order to examine the effects of AoA, derived from children's naming performance (the so-called objective AoA norms) which, as we have shown, are less correlated with word frequency (and other variables) than rated AoA. It is important to determine whether controlling for cumulative frequency would have the effect of removing AoA effects. However, as we have argued above, finding AoA effects using either rated or objective AoA measures,

[1] These analyses have also been performed with subjective frequency (using scores taken from Bonin et al., 2003) included as a predictor as Zevin and Seidenberg (2002) have done. The patterns of results were highly similar and subjective frequency was reliable in all analyses. However, in these analyses and the subsequent ones performed in the current paper, we have noted that subjective frequency estimates were highly related to conceptual familiarity, AoA (when included in the analyses) and cumulative frequency. These intercorrelations give rise to multicolinearity problems, with the result that a high instability is introduced, more particularly regarding conceptual familiarity and cumulative frequency which were not significant in several analyses reported hereafter. For this reason, the following analyses reported in the paper do not include the subjective frequency variable.

and with cumulative frequency controlled, may not necessarily be taken as evidence for 'real' AoA effects in word reading and other tasks given the circularity problem. Therefore, and most importantly, we also examine whether frequency trajectory has a reliable contribution in word reading over and above cumulative frequency and other lexical variables. Indeed, as Zevin and Seidenberg (2002) have argued, the critical test of age-limited learning effects is the finding of an effect of frequency trajectory. Therefore, we will also report some re-analyses of previous published data of our own in spoken and written picture naming (from Bonin et al., 2002), spelling to dictation (from Bonin & Méot, 2002) and lexical decision (from Bonin et al., 2001a) in order to test the generality of the influence of frequency trajectory and cumulative frequency in a number of lexical processing tasks. It is important to note that, with the exception of the spelling to dictation task (where only monosyllabic words were used), the majority (164/179) of the words used in the analyses of the different tasks were the same.

A multiple regression study of AoA and word frequency

In their connectionist modeling work of word reading, Zevin and Seidenberg's (2002) simulations did not show any influence of frequency trajectory when cumulative frequency was controlled and when the network encoded the quasi-regular mappings between spelling and sound units that exist in English orthography. This observation was interpreted as being strongly supportive of the view that long lasting effects of age-limited learning—AoA effects—are not real in word reading. However, cumulative frequency did have long lasting effects on the network's performance, so that high-frequency items are better encoded than low-frequency items. Zevin and Seidenberg found that frequency trajectory had an effect in their simulations only when what is learned about early patterns does not carry over to later ones, a condition which, they argue, is not characteristic of learning spelling-sound mappings but may be relevant in other tasks (such as learning the names of objects or faces). Thus, according to Zevin and Seidenberg (2002), frequency trajectory effects should be observed in tasks in which the mappings between different codes are arbitrary, as is the case in picture naming, which is a semantically mediated task (Levelt, Roelofs, & Meyer, 1999) that involves the largely arbitrary mappings between semantic and lexical representations. For example, whereas knowing the pronunciation of the words *cat* and *hat* might assist reading the word *bat*, knowing the names of the objects *CAT* and *HAT* could not help naming related objects (such as *DOG* or *CAP*).

In this experiment, a large number of words were presented for oral reading and naming latencies were analysed using multiple regression. It has been known and accepted for some time that the multiple regression approach presents a number of problems, such as the possibility of suppressing predictor variables because of their correlations with other variables (Morris, 1981) and 'noise' in the measurements used. An implicit claim has therefore been that factorial designs (which attempt to manipulate one variable while holding others constant) should be preferred over regression-based designs. However, it is often difficult to control for all the other important potential factors influencing the dependent variable, particularly so for word reading where measures of AoA and word frequency are both correlated with each other and with a large number of other characteristics of the words, and so factorial designs sometimes result in comparisons between small and unrepresentative samples of words. Whereas some studies have included unmatched factors as covariates in factorial designs, the problem of suppressing predictor variables due to their correlation with other variables persists.

It is important in multivariate studies to include most of the essential variables that might be expected to have some effect on word naming times. Therefore, the various factors that we examined were: both rated and objective AoA; frequency trajectory and cumulative frequency; the semantic variables of imageability, concreteness, and conceptual familiarity; the orthographic variables of bigram frequency, number of orthographic neighbors, and word length; and a number of measures of the features of the initial phonemes of the words. It is important to include these initial phoneme characteristics (such as whether they are voiced, etc.) since Treiman, Mullenix, Bijeljac-Babic, and Richmond-Welty (1995) found that they make a strong contribution to predicting word naming latencies (see also Morrison & Ellis, 2000).

Method

Participants

The participants were 36 psychology students of Blaise Pascal University who received course credit for participating. All were native speakers of French and had normal or corrected-to-normal vision.

Stimuli

The experimental stimuli were 200 words, although, as values for some independent variables were not available for 10 words, only 190 were analysed. The statistical characteristics of the critical 190 words are shown in Table 2 and the Appendix lists these words (along with the mean naming latency for each). No frankly irregular words were included and all the words used were object names (i.e., concrete nouns).

Cumulative frequency and frequency trajectory were computed as described earlier. AoA ratings were taken from Alario and Ferrand (1999) and the objective AoA

Table 2
Characteristics of the words used in the multiple regression study of word reading

	Mean	*SD*	Minimum–maximum
Objective AoA (months)	58.6	23.98	32.5–140.5
LEXIQUE word frequency	36.0	67.75	0.26–476.97
Log (1 + LEXIQUE)	1.17	.56	.10–2.68
MANULEX word frequency (*U*)	93.12	136.17	.05–927.26
Log *U* MANULEX	1.66	.55	.02–2.97
MANULEX word frequency	205.77	278.31	2.00–1847
Log (1 + MANULEX)	2.04	.51	.48–3.27
Cumulative frequency (*z* scores)	0.00	1.82	−4.88–4.74
Frequency trajectory	0.00	.80	−1.71–3.08
Number of phonemes	4.45	1.40	2.00–9.00
No. of orthographic neighbors	1.96	2.56	0–14
Bigram frequency	1197.0	655.5	82.5–4028
Conceptual familiarity	3.11	1.23	1.07–4.97
Imageability	4.59	.29	2.60–5.00

Notes. Objective AoA taken from Chalard et al. (2003); LEXIQUE word frequency taken from New et al. (2001); MANULEX word frequency taken from Lété et al. (in press). No., number; Bigram frequencies calculated from Content and Radeau (1988); Conceptual familiarity taken from Alario and Ferrand (1999) and imageability taken from Bonin et al. (2003).

measures were taken from Chalard et al. (2003). Conceptual familiarity values were taken from Alario and Ferrand (1999), and imageability and concreteness ratings were taken from Bonin et al. (2003). Each word's number of orthographic neighbors (i.e., the number of different words that can be created by changing one letter of the target word, while preserving letter positions) were obtained from Content et al. (1990), and mean bigram frequencies were calculated from Content and Radeau (1988). Eleven initial phoneme features (coded as 0 or 1 on each feature) were used as predictors following Treiman et al.'s (1995) classification; the semivowel feature was not included because no word began with a semivowel.

Procedure

All participants were tested individually in one session which lasted about 40 min. The experiment was run using PsyScope version 1.2 (Cohen, McWhinney, Flatt, & Provost, 1993) on an Apple PowerMac computer. The computer controlled the presentation of the words and recorded the naming latencies to the nearest millisecond from an AIWA CM-T6 small tie-pin microphone connected to the computer via a button-box. Each word was presented in the centre of the computer screen (in 48-point Chicago font) and participants were instructed to read it aloud, as quickly as possible. The order of presentation of the words was random. Each trial began with a visual ready signal ("*") presented on the screen for 500 ms, followed by the stimulus word, which remained in the centre of the screen until the participant's response. The next trial was initiated 5 s later. The experiment started with 10 practice trials (using additional words not included in the experimental list).

Results and discussion

Word reading times were excluded from the analyses if a technical problem occurred, if participants stuttered or produced sounds such as mouth clicks or various dysfluencies (such as saying "um" or "er"), or if the word was read incorrectly. Further, responses exceeding two standard deviations above the item means were also excluded (1.03%). Overall, 2.66% of all observations were discarded.

Table 3 shows the correlations between word naming latencies and the major lexical variables. The independent variable that had the highest correlation with naming latencies was MANULEX frequency, followed (in rank order) by cumulative word frequency, phonological length, rated AoA, LEXIQUE frequency, number of orthographic neighbors, objective AoA, conceptual familiarity, and bigram frequency.

Four simultaneous multiple regression analyses were performed using naming latencies as the dependent variable. The predictors that were common to all four analyses were: cumulative frequency, conceptual familiarity, imageability, concreteness, number of orthographic neighbors, bigram frequency, length in phonemes, and the 11 phoneme features. Regression 1 included objective AoA and regression 2 included rated AoA. Regression 3 included frequency trajectory and objective AoA, and regression 4 included frequency trajectory but no AoA measures.

The overall regression equations were all significant: (1) $F(18,156) = 22.17$; (2) $F(18,156) = 20.63$; (3) $F(19, 155) = 21.0$; and (4) $F(18,156) = 20.66$ ($p < .001$ for all analyses). As a perfect colinearity relationship occurred between the initial phoneme features, the fricative feature was removed from the analyses. It should be noted that

Table 3
Correlations among the 'lexical' predictors and word naming latencies (NL)

	NL	LEXIQUE	MANULEX	CumF	Ftraj	Rated AoA	Obj AoA	Fam	Imag	*N*	Bigram	Phons
LEXIQUE	−.313*											
MANULEX	−.402*	.680*										
Cum Freq	−.390*	.916*	.916*									
Freq Traj	.111	.400*	−.400*	.000								
Rated AoA	.345*	−.496*	−.668*	−.635*	.215*							
Obj AoA	.273*	−.277*	−.537*	−.444*	.325*	.678*						
Fam	−.203*	.533*	.233*	.418*	.374*	−.576*	−.287*					
Imag	−.134	.027	.305*	.181*	−.347*	−.470*	−.543*	.204*				
N	−.298*	.264*	.175*	.240*	.111	−.173*	.014	.127	−.149*			
Bigram	−.168*	.056	.061	.063	−.006	−.083	−.101	.045	−.059	.190*		
Phons	.348*	−.339*	−.278*	−.337*	−.077	.273*	.043	−.125	.079	−.504*	.043	
Con	.045	−.324*	−.153*	−.260*	−.213*	−.070	−.091	.005	.406*	.002	.021	.153*

Notes. Cum Freq, cumulative frequency; Freq Traj, frequency trajectory; AoA, age-of-acquisition; Fam, conceptual familiarity; Imag, imageability; *N*, number of orthographic neighbors; bigram, bigram frequency; Phons, number of phonemes; Con, concreteness.
* Significant at $p < .05$.

these initial phoneme characteristics were included both to get a more reliable estimation of the variance explained by random fluctuations and to avoid the problem of confounding explained variance related to lexical variables with the specific variance related to these features. However, the correlations between the initial phoneme characteristics and the lexical variables were very low (the maximum of the R^2 between any of the variables of interest and any of the initial phoneme characteristics was .176), which suggests that the confounding was very low. For the sake of conciseness, the results concerning the initial phoneme characteristics are not reported in the tables summarizing the regression analyses. However, all the initial phoneme characteristic measures were significant in the four regressions, with the exceptions of the bilabial feature in all the regression equations, the stop consonant feature in regressions 1, 3, and 4, and the velar feature in regressions 3 and 4. In fact, these features made a strong contribution to predicting naming latencies, as they accounted for between 43.4% (in regression 4) and 45.8% (in regression 1) of the variance. The effects due to these characteristics of the initial phonemes of words can be attributed to the ease (or power) to stop the voice key for articulatory responses.

In all four regressions, there were significant effects of phonological length, bigram frequency and cumulative frequency (Tables 4 and 5). Objective AoA was significant in regression 1, but rated AoA was not reliable in regression 2, which is also what Zevin and Seidenberg (2002) found. Objective AoA was also significant in regression 3, in which frequency trajectory was included. Thus, controlling for cumulative frequency does not always result in the removal of a reliable effect of AoA. That objective AoA had a reliable effect when cumulative frequency was also taken into account may be due to the fact that it is less related to the other predictors (and to reading latencies) than rated AoA. (Note also that objective AoA, but not rated AoA, was predicted by adult picture naming times.)

Frequency trajectory made no reliable contribution to word naming times in either regression 3 or 4 (Table 5). This is an important result given that Zevin and Seidenberg (2002) argued that this variable is the best (and critical) test of age-limited learning effects in oral word reading latencies. However, a concern with Zevin and Seidenberg's analyses is worth mentioning here. They conducted multiple regression analyses of 528 words (for which rated AoA values were available in the norms provided by Gilhooly & Logie, 1980) from two large-scale studies of word reading (Seidenberg & Waters, 1989; Spieler & Balota, 1997) and a large-scale study of lexical decision (Balota et al., 2001). Zevin and Seidenberg assessed the amount of unique variance associated with AoA and word frequency (using the WFG norms) after other lexical variables (imageability, lexical familiarity, concreteness, length, and number of orthographic neighbors) were partialled out. They found that

Table 4
Significant predictors in regressions 1 and 2

	Objective AoA				Rated AoA			
	$R^2 = .719$				$R^2 = .704$			
	β	SE	t	p	β	SE	t	p
Cum Freq	−.145	.059	−2.466	.015	−.159	.064	−2.467	.015
AoA	.197	.059	3.335	.001				
Bigram	−.173	.047	−3.678	.0001	−.185	.048	−3.846	.0001
Phons	.228	.054	4.203	.0001	.211	.056	3.732	.0001

Notes. Cum Freq, cumulative frequency; AoA, age-of-acquisition; Bigram, bigram frequency; Phons, number of phonemes.

Table 5
Significant predictors in regressions 3 and 4

	Objective AoA				No AoA			
	$R^2 = .72$				$R^2 = .704$			
	β	SE	t	p	β	SE	t	p
Cum Freq	−.142	.059	−2.401	.018	−.193	.058	−3.340	.001
AoA	.182	.062	2.955	.004				
Bigram	−.172	.047	−3.648	.0001	−.187	.048	−3.897	.0001
Phons	.227	.054	4.184	.0001	.225	.056	4.043	.0001

Notes. Cum Freq, cumulative frequency; AoA, age-of-acquisition; Bigram, bigram frequency; Phons, number of phonemes.

word frequency accounted for a small but reliable amount of variance in each study, whereas rated AoA did not. A problematic aspect of Zevin and Seidenberg's analyses is that they did not include characteristics of the words's initial phonemes as predictors in their regression analyses. Given the tenuous relationships of these variables with the lexical predictors, this has no important consequences for the estimations of the effects or the percentages of unique variance, but it can have an effect on tests of significance. We found that the percentages of variance explained by the initial phoneme characteristics were roughly equal to .45, which is rather high. Furthermore, in all the regression equations the R^2 were roughly equal to .70, which is similar to the Morrison and Ellis (2000) study but very different from what Zevin and Seidenberg reported (.17 for Seidenberg and Waters and .25 for Spieler and Balota). As a result, the residual sum of squares were 'mechanically' more important in their analyses. With a variance comparison basis for testing effects so far from a pure measure of random effects affecting reaction times, the F-values for testing individual effects were mechanically underestimated in the Zevin and Seidenberg analyses. For example, if we suppose that in their analyses, the R^2 between the lexical independent variables plus the initial phoneme characteristics[2] is roughly equal to .70 (in accordance with both the results of our study and that of Morrison & Ellis, 2000), then the application of Cohen and Cohen's (1983) formula (p. 107)[3] yields the following F-values for testing AoA effects: 4.93 in the Spieler and Balota (1997) study and .17 in the Seidenberg and Waters (1989) study. (The Balota et al. lexical decision study was not considered because initial phoneme features do not play a significant role in this task, see Morrison & Ellis, 2000.) Hence, in one of the two word reading studies, the contribution of rated AoA in word reading latencies would be reliable if it were tested with a more adequate measure of variability associated with random fluctuations.

Frequency trajectory effects in lexical processing: Re-analyses of some previous data

We now report some re-analyses of the data from previous published studies of our own in spoken and written naming, spelling to dictation and lexical decision. Most of these studies were conducted before the MANULEX child frequency database was available and before the notion of frequency trajectory had been introduced. In all the regression analyses, cumulative frequency and frequency trajectory (as used in the analyses of word reading reported earlier) were introduced as predictors together with other relevant variables for each task. The purpose of these analyses was to assess the generality of any effect of frequency trajectory

[2] We used seven independent variables plus ten initial phoneme characteristics in our analyses.

[3] In the formula, sr^2 corresponds to the unique variance given by Zevin and Seidenberg (2002).

in lexical processing tasks that vary in the degree of predictability of the mapping relationships between input and output representations. Spelling, like reading, entails quasi-regular orthography–phonology mappings whereas object naming entails essentially arbitrary mappings between semantic and lexical mappings. As for our study of word reading latencies, regression analyses were performed with either rated or objective AoA or without any AoA measures.

Spoken and written picture naming

Bonin et al. (2002) performed regression analyses on both oral and written naming latencies to a large set of pictures taken from the Snodgrass and Vanderwart (1980) studies. They reported effects of AoA, image variability and image agreement, but found no effect of word frequency (as assessed by the BRULEX database). In the re-analysis of these naming data, we included the measures of cumulative frequency (instead of BRULEX frequency) and frequency trajectory, and also included name agreement, image agreement, visual complexity, conceptual familiarity, imageability, word length (number of phonemes in spoken naming and number of letters in written naming), bigram frequency, and concreteness. Analyses were performed with either rated AoA or objective AoA included, or without AoA.

Table 6 shows the results for the spoken naming task. The equation including objective AoA produced the highest explanatory power and showed a reliable effect of this variable. (This result is not surprising given that, as discussed earlier, objective AoA derived from children's performance is related to adult naming performance.) As for reading aloud words, there was no reliable effect of rated AoA. There was a reliable effect of frequency trajectory when rated AoA was included and when no AoA measure was included; it was not significant when objective AoA was included. When no AoA measures were included, there was a reliable effect of cumulative frequency, a result which contrasts strongly with analyses reported in Bonin et al. (2002). The results for the written naming task (shown in Table 7) were very similar to those for oral naming, both in terms of the overall explanatory power of the regression equations and the variables that had reliable effects.

Spelling to dictation

Spelling to dictation in alphabetic orthographies is, like word reading, a task that involves mappings between phonology and orthography. In French, sublexical phonology-to-orthography correspondences in spelling are much less consistent than orthography-to-phonology correspondences in reading (Peereman & Content, 1999). The same is also true for English (e.g., Barry & Seymour, 1988). However, although

Table 6
Significant predictors in the spoken naming picture task

	Rated AoA				Objective AoA				No AoA			
	$R^2 = .365$, $F(11, 164) = 8.556$				$R^2 = .57$, $F(11, 164) = 19.771$				$R^2 = .364$, $F(10, 165) = 9.462$			
	β	SE	t	p	β	SE	t	p	β	SE	t	p
AoA					.657	.074	8.857	.0001				
Cum Freq									−.182	.082	−2.217	.028
Freq Traj	.196	.093	2.116	.036					.207	.079	2.601	.010
NA	−.217	.064	−3.376	.001	−.159	.053	−3.01	.003	−.218	.063	−3.442	.001
IA					−.119	.056	−2.145	.033				
Fam	−.246	.106	−2.308	.022					−.258	.090	−2.865	.005
Imag	−.224	.087	−2.580	.011					−.229	.083	−2.745	.007

Notes. AoA, age-of-acquisition; Cum Freq, cumulative frequency; Freq Traj, frequency trajectory; NA, name agreement; IA, image agreement; Fam, conceptual familiarity; Imag, imageability.

Table 7
Significant predictors in the written naming picture task

	Rated AoA				Objective AoA				No AoA			
	R^2 =.387, $F(11,157) = 9.014$				R^2 =.554, $F(11,157) = 17.695$				R^2 =.385, $F(10,158) = 9.873$			
	β	SE	t	p	β	SE	t	p	β	SE	t	p
AoA					.586	.076	7.708	.0001				
Cum Freq									−.177	.084	−2.111	.036
Freq Traj	.189	.093	2.027	.044					.227	.080	2.825	.005
NA	−.143	.065	−2.198	.029					−.150	.064	−2.329	.021
IA	−.139	.069	−2.026	.044	−.142	.058	−2.447	.016				
Fam	−.233	.107	−2.168	.032					−.278	.091	−3.043	.003
Imag	−.261	.086	−3.024	.003					−.278	.084	−3.322	.001

Notes. AoA, age-of-acquisition; Cum Freq, cumulative frequency; Freq Traj, frequency trajectory; NA, name agreement; IA, image agreement; Fam, conceptual familiarity; Imag, imageability.

inconsistent, the relationships between phonology and orthography are not arbitrary but are quasi-regular. A straightforward prediction from Zevin and Seidenberg's (2002) approach is that frequency trajectory should not have a reliable influence in spelling to dictation, but cumulative frequency should. Bonin and Méot (2002) performed regression analyses on the written spelling latencies corresponding to a set of about 150 monosyllabic words, and found that there were significant effects of the acoustic duration of the words, rated AoA, LEXIQUE word frequency, phonology-to-orthography consistency (of the rimes) and number of letters. (There were no reliable effects of number of phonological neighbors or imageability.) Given the concerns regarding AoA measures (and the use of adult frequency alone), the AoA effect found in the Bonin and Méot (2002) in spelling to dictation must be considered to be questionable.

In our re-analyses, we used cumulative frequency (instead of adult frequency) and frequency trajectory, and also included conceptual familiarity, concreteness and bigram frequency. The analyses were performed with or without rated AoA, but not with objective AoA as these norms were not available for the majority of the items.

Table 8 shows that cumulative frequency was not reliable when rated AoA was included in the equation, but was significant when no AoA measure was included. Importantly, frequency trajectory was not reliable in either analysis.

Lexical decision

It has been assumed that the lexical decision task is performed on some measure of familiarity of the items, computed from a variety of orthographic, phonological and semantic codes (e.g., Plaut, 1997). Interestingly, some authors (e.g., Morrison & Ellis, 2000; Plaut, 1997) have assumed that semantic codes are consulted in lexical decisions. If lexical decisions require the use of semantics in order to distinguish words from orthographically legal nonwords, then performance in this task might also be sensitive to age-limited learning effects and so show an effect of frequency trajectory.

Bonin et al. (2001a) collected visual lexical decision times to a set of about 200 words and reported that there were significant effects of AoA, adult word frequency and word length. They also reported an interaction between the two variables, as the effect of AoA was observed on low-frequency but not on high-frequency words. (There was also an effect of bigram frequency, although this did not reach significance when the multiplicative term corresponding to the interaction between AoA and word frequency was included.) In our re-analyses, we used cumulative frequency (instead of adult frequency), frequency trajectory, conceptual familiarity, imageability, image variability, bigram frequency, number of orthographic neighbors, and word length (in letters), but did not include grapheme-to-phoneme regularity (as this is only an approximate measure of orthography-to-phonology consistency).

As shown in Table 9, the patterns of significant effects were very similar for both measures of AoA and, in contrast to the results for word reading and picture naming, the explanatory power of the equations both for rated and objective AoA was very similar. Cumulative frequency had a consistently reliable effect but frequency trajectory was significant only when no AoA measure was included.

Discussion

These re-analyses showed that there were reliable effects of both cumulative frequency and frequency trajectory on picture naming latencies (as well as effects of name agreement, familiarity, and imageability). The inclusion of AoA tended to mask these effects, which was particularly true when objective AoA was used (which, as we have shown earlier, are likely to be due to the performance measure aspect of this variable). As for our

Table 8
Significant predictors in the spelling to dictation task

	Rated AoA				No AoA			
	$R^2 = .538$, $F(10,153) = 17.85$				$R^2 = .486$, $F(9,154) = 16.185$			
	β	SE	t	p	β	SE	t	p
AoA	.418	.100	4.166	.0001				
Cum Freq					−.323	.073	−4.449	.0001
Letters	−.137	.067	−2.043	.043	−.184	.070	−2.636	.009
PO-VC	−.162	.066	−2.459	.015	−.179	.069	−2.592	.010
AD	.668	.064	10.470	.0001	.678	.067	10.101	.0001

Notes. AoA, rated age-of-acquisition; CumF, cumulative frequency; Letters, number of letters; PO-VC, PO consistency of the rime units; AD, acoustic duration.

Table 9
Significant predictors in the lexical decision task

	Rated AoA				Objective AoA				No AoA			
	$R^2 = .589$, $F(10,163) = 23.35$				$R^2 = .580$, $F(10,163) = 22.545$				$R^2 = .569$, $F(9,164) = 24.094$			
	β	SE	t	p	β	SE	t	p	β	SE	t	p
AoA	.263	.095	2.783	.006	.150	.073	2.068	.040				
Cum Freq	−.270	.075	−3.605	.0001	−.316	.071	−4.424	.0001	−.362	.069	−5.284	.0001
Freq Traj									.142	.067	2.124	.035
Fam					−.156	.070	−2.217	.028	−.92	.069	−2.785	.006
Imag									−.170	.068	−2.511	.013
Letters	.354	.065	5.477	.0001	.383	.065	5.896	.0001	.374	.066	5.712	.0001
Bigram	−.187	.052	−3.584	.0001	−.186	.053	−3.499	.001	−.202	.053	−3.801	.0001

Notes. AoA, age-of-acquisition; Cum Freq, cumulative frequency; Freq Traj, frequency trajectory; Fam, conceptual familiarity; Letters, number of letters; Bigram, bigram frequency.

study of oral reading, there was no reliable contribution of frequency trajectory to spelling to dictation latencies, but there were significant effects of cumulative frequency, word length (both acoustic duration and number of letters) and the phonology-to-orthography consistency of the rime of the words. For lexical decision latencies, there were reliable effects of both cumulative frequency and frequency trajectory. However, if we compare the β coefficients, and the p values[4] of the analysis of lexical decision times with those found in the analysis of picture naming (and given that no frequency effect was found when rated AoA was included), frequency trajectory appears to be less influential in lexical decision than in picture naming.

Cumulative frequency was significant for all tasks, including picture naming, which is contrary to the conclusions presented in Bonin et al. (2002) who used only an 'adult' measure of frequency. In contrast, frequency trajectory, which can be seen as a more direct (and 'uncontaminated') measure of age-limited learning, revealed dissociations between the tasks: it had reliable effects in both oral and written picture naming (and, but to a smaller extent, in lexical decision), but no effects in spelling to dictation and oral word reading. These results are consistent with the general theoretical claim that age-limited learning effects are found when the mapping relationships between input and output representations are arbitrary (as for naming) but not when they are quasi-regular (as for reading and spelling).

[4] Given the differences of independent variables used in the two tasks, this comparison can be seen as a rough indicator of the difference.

General discussion

The aim of the present study was to advance the work initiated by Zevin and Seidenberg (2002) regarding AoA (or age-limited learning) effects in word reading and other lexical tasks. Zevin and Seidenberg's methodological critique of a number of reported claims of AoA effects in oral reading showed that the early and late acquired words studied were not matched for cumulative frequency as assessed from large and representative measures of frequency that sample texts to which children are exposed. In their multiple regression analyses of the data from large-scale studies of word reading times, they also showed that there was no reliable, independent contribution of AoA to word reading latencies. We questioned some aspects of their analyses, which did not appear to have included variables relating to features of the initial phonemes of the words that account for fairly substantial proportions of the variance in reading times. As a result, the contribution of AoA to reading times in Spieler and Balota's (1997) study would have been reliable if tested with a more adequate measure of the variability associated with random fluctuations. Therefore, controlling for cumulative frequency does not necessarily result in the elimination of an effect of AoA, which highlights a danger of arguing from null effects of rated AoA.

Zevin and Seidenberg (2002) also argued that objective AoA measures derived from the study of when children can name objects should be seen as essentially a performance measure, which leads to the serious *circularity* problem. This is the difficult issue of whether some words are 'easy' to process because they are acquired early in life, or whether words are acquired early because of factors that make them 'easy.' The inter-correlated nature of the candidate variables that are likely to make words 'easy' to process in adulthood (such as frequency, concreteness, length, and even age, or order, of acquisition) severely complicates empirical attempts to address this central issue. Furthermore, at a theoretical level, the question of *why* some words are learned earlier in life than others has, unfortunately, been rather neglected in the AoA literature.

Zevin and Seidenberg's (2002) suggested solution to the circularity problem was to examine the effects of *frequency trajectory*. They suggested that some words will be acquired earlier in life because they are encountered more frequently than others in the texts to which children are exposed while learning to read. (This further emphasizes the importance of the use of 'child' measures of word frequency in this area of research.) Frequency trajectory, therefore, can be used as an objective measure of real age-limited learning effects in reading (and one less contaminated by other correlated variables than AoA measures). Our analyses of frequency trajectory (calculated by the difference between *z*-scores of recently available 'child' and 'adult' frequency corpora in French) support their view. We found that frequency trajectory has a reliable effect on both adult AoA ratings and the AoA measure derived from children's object naming performance (which is in line with what Zevin & Seidenberg found in English), and so is a factor that influences the order of acquisition of French words. Our analyses also showed that rated AoA is more affected by other lexical properties than is objective AoA. Importantly, these analyses validate the use of frequency trajectory as a tool to investigate age-limited learning effects in lexical tasks. The use of frequency trajectory as computed here is also interesting regarding its relationship with cumulative frequency: given that the correlation between the two variables is extremely small, from a technical point of view it permits a better estimation of their independent effects, and so provides a solution to the perennial problem in the AoA literature of the correlations between rated or objective AoA and word frequency.

Frequency trajectory is therefore a measure with the potential to advance research and achieve clarity in the AoA literature, for a number of reasons: (i) it is theoretically motivated, as it offers a plausible reason for why some words are learned earlier than others; (ii) it is empirically defensible, as it accounts for a significant portion of the variance in AoA measures and is less correlated with other lexical properties than AoA; and (iii) it is an objective property of words (derived from child and adult frequency norms) and so is not subject to the criticism that it is a performance variable. As such, finding an effect of frequency trajectory can be seen to be the critical test of age-limited learning effects, which is the essential AoA hypothesis. We examined frequency trajectory effects in our multiple regression study of French word reading latencies and also in our re-analyses of the data from previous studies of spoken/written naming, spelling and lexical decision. The results from all five tasks are summarized in Table 10. In the table the "yes" entries correspond to cases involving semantic codes, consistent with Zevin and Seidenberg's hypothesis.

We found that cumulative frequency had a reliable effect on French word reading times (in addition to effects of word length and bigram frequency), but frequency trajectory did not. There remained a reliable effect of objective AoA even when both cumulative

Table 10
Summary of the results concerning the contribution of frequency trajectory as a function of task and the nature of the mapping involved in the task

Task	Mapping	Frequency trajectory effect
Word naming	Orthography → Phonology	No
Spoken picture naming	Semantics → Phonology	Yes
Written picture naming	Semantics → Orthography	Yes
Spelling to dictation	Phonology → Orthography	No
Lexical decision	Orthography → Semantics	Yes

frequency and frequency trajectory were included in our regression 3. This shows that the inclusion of cumulative frequency does not necessarily result in eliminating an AoA effect on reading. However, it is less clear why our observed objective AoA effect persists when we found no effect of frequency trajectory. One possible reason is that it reflects a statistical artefact; as it is a performance variable, objective AoA is more related to other factors that affect reading times than is frequency trajectory. However, many of these other variables (such as imageability and familiarity) which influence AoA, were also included in the multiple regression and had no independent effect. Of course, it is possible that this AoA measure is still picking up some variance due to other performance aspects that also affect reading times, but the possibility remains that it reflects a genuine *age* of acquisition effect that operates over and above that of frequency trajectory, perhaps resulting from aspects of the learning of words before the acquisition of reading. AoA and frequency trajectory are not "the same thing." Our measure of frequency trajectory derives from texts used in primary school but children will have learned many words before they begin to be exposed systematically to such printed texts. Clearly, more detailed experimental study will be required to demonstrate any such effect conclusively, and we accept Zevin and Seidenberg's claim that frequency trajectory is a better test of age-limited learning effects than the AoA measures used so far.

Given this acceptance, the second major goal of our study was to examine frequency trajectory effects in other lexical tasks in addition to reading aloud. Such an examination across different tasks represents an important test of the generality of theoretical accounts from connectionist models concerning whether the mappings between different input and output codes used are quasi-regular or arbitrary. The results of the re-analyses of some of our previously reported studies were clear-cut: frequency trajectory affected both spoken and written picture naming latencies and (to a lesser extent) lexical decision times, but had no effect on spelling to dictation latencies. Cumulative frequency affected all tasks. We submit that we have therefore achieved an empirical resolution of the role of AoA and are now in a position to discuss theoretical interpretations of AoA and frequency effects in word reading, lexical decision, picture naming, and spelling to dictation.

Several different functional loci have been proposed for AoA effects (see De Moor, Ghyselinck, & Brysbaert, 2001). A number of authors have proposed that AoA effects are located at the retrieval of lexical phonology. Brown and Watson's (1987) phonological completeness hypothesis proposed that words acquired early in life have phonological representations which are holistic in nature whereas later acquired words are stored in some more fragmented fashion (and so take more time to be assembled for production). However, recent data from Monaghan and Ellis (2002b) contradicts this account, as they found that early acquired words were no easier to segment in phonological awareness tasks than late acquired words. Brysbaert et al. (2000b) suggested a semantic locus of AoA effects. Izura and Ellis (2002) found an AoA effect in lexical decision times to words in the second language (acquired after childhood) of Spanish-English bilinguals, but the words do not appear to 'inherit' any AoA advantage from any semantically based representations from their first language. Izura and Ellis argued that AoA effects really reflect the *order* of word acquisition.

AoA effects have been simulated in connectionist models. Ellis (2002, Ref. Note 2) identified two approaches to modeling AoA in neural networks. In one, training is cumulative with a steadily increasing 'vocabulary' of items introduced during learning. Ellis and Lambon Ralph (2000) used this approach in models with distributed representations that learned by back-propagation. They suggested that AoA effects reflect a natural, emergent property of adaptive networks in which learning is cumulative and interleaved. AoA effects result from the gradual loss of plasticity in such networks and are located in the strength of the connections relating different kinds of representations involved in word processing tasks. The items learned first produce the most important changes in the network's connection weights and so later learned items are forced to adapt to the structure already generated. Ellis and Lambon Ralph's simulations always showed effects of both AoA and word frequency, although the AoA effects tended to be larger in magnitude. Monaghan and Ellis (2002a) extended this approach and found that their model showed large AoA effects when the mappings between input and output patterns are arbitrary and only small effects when they are more consistent (as Zevin & Seidenberg, 2002, also showed).

In the other approach, all items are trained together from the outset (Anderson & Cottrell, 2001; Smith, Cottrell, & Anderson, 2001). Smith et al. have shown that AoA effects can be observed when all patterns are presented in this way. AoA was measured for each pattern individually as the time during training when the pattern is learned. An item was considered to be learned when its error fell below a threshold value and learning continued until error reached minimum. Smith et al. found that some items reached threshold quickly whereas others took longer. Using this operationalization of AoA for the items trained, AoA effects were found on the residual error of a pattern after training is complete, so that early learned items go on to have smaller final error values than late learned items: AoA effects were due to differences in *learnability*. According to this view, AoA effects are due to early learned items having 'better' representations than late learned items. However, this leaves open the question of exactly makes some items easier to learn.

The connectionist models of Ellis and Lambon Ralph (2000) and Smith et al. (2001) involved the learning of artificial patterns (such as binary sequences) which may limit generalizing their results to a range of lexical tasks. Zevin and Seidenberg (2002) presented a connectionist model of word reading which implemented the quasi-regular relationships that exist between orthographic and phonological units in alphabetic languages, and used real words to do so. In this model, word identification and pronunciation are the result of the development of distributed patterns of activation spread among a large number of units and all parts of the system participate in processing a word. Learning is continuous, so every word influences the weight of the connections, and patterns that appear more frequently will have more impact on the network. The model is sensitive to both the number of exposures to words and the systematicity of the mappings between their input (spelling) and output (pronunciation). Thus, cumulative word frequency, as well as the consistency between spelling and sound units, is encoded in the weights relating different sub-word representations. An important property of such models is that what is learned about one word carries over to others with which it shares common features. Effects arising from frequency of exposure are modulated by the consistency of spelling-to-sound mappings, so that there are larger effects of frequency for words whose mappings are less systematic (e.g., inconsistent words).

There were no age-limited learning effects in Zevin and Seidenberg's (2002) model because, given the quasi-systematic relationships of English orthography it encoded, the changes in the weights that occur when a word is trained would also benefit all words with which it overlaps. They trained networks with orthographic input units, phonological output units, hidden units and clean-up units. The connections were feed-forward, except for the clean-up units which were connected bidirectionally with the phonological units. Zevin and Seidenberg considered frequency trajectory in order to test for any AoA contribution. Some 'early' patterns were presented frequently at the beginning of training and then their frequency of presentation decreased, whereas the symmetrical manipulation was made for other 'late' patterns whose cumulative frequency was matched by the end of training. Their simulations showed that there was no effect of frequency trajectory but there was a significant effect of cumulative frequency. However, frequency trajectory did make a reliable contribution when there were no obvious regularities in the mappings between input and output patterns, when the network was forced, in effect, to memorize individual patterns. Thus, connectionist networks show a frequency trajectory effect when the mappings between input and output representations are arbitrary.

We found an effect of frequency trajectory in our reanalysis of the lexical decision data of Bonin et al. (2001a), although we found no such effect on oral reading latencies. Both connectionist (Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989; Zevin & Seidenberg, 2002) and dual-route (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) models of visual word recognition attempt to account for both reading aloud and lexical decision performance. It is generally assumed that lexical decisions are performed on the basis of some index of familiarity constructed from several types of codes, including semantic codes when the orthographic and phonological codes are not sufficient to distinguish efficiently words from nonwords. Plaut (1997) provided a computational analysis of the lexical decision task within connectionist models that implement semantics which suggests that people consult semantic information when the nonwords are highly word-like (e.g., pseudohomophones) or when the words are orthographically strange. The nonwords used by Bonin et al. (2001a) were very word-like; they were created by selecting for each word another word having the same length and frequency and then substituting a letter that results in a nonword. For example, the French word *pomme* (apple) was yoked with the word *plume* (feather) yielding the nonword *plude*. The use of such nonwords, which would encourage the involvement of semantic information, may account for our observation of age-limited learning effects in the lexical decision task. If frequency trajectory may be seen as an index of the involvement of arbitrary mappings, then the implication is that the lexical decision task can, under certain conditions, involve orthographic–semantic–phonological mappings. The notion that semantics was involved is supported by our finding that both conceptual familiarity and imageability, variables that are assumed to index semantic involvement (e.g., Strain, Patterson, & Seidenberg, 1995, 2002), had reliable effects on lexical decision performance. Although the modeling work of Zevin and Seidenberg (2002) was not intended to account for the lexical decision task, connectionist models of this kind (e.g., Plaut et al., 1996) are able to account for the influence of frequency trajectory effects in lexical decision given that they include a semantic-to-phonology pathway that can exert an influence in this task.

Taken together, the findings from the lexical decision and word reading tasks reported here challenge Gerhand and Barry's (1999b) account of word frequency and AoA effects in lexical decision. They proposed that the effect of AoA was ascribed to lexical phonology whereas word frequency would be ascribed to the visual recognition process itself. Apart from the confound of AoA with WFG frequency in this study identified by Zevin and Seidenberg (2002), the results we have presented here do not accord with the notion of separate loci for AoA and cumulative frequency effects in lexical decision, especially as word reading and lexical decision both involve an initial stage of word recognition.

It is not entirely clear how models of visual word recognition that contain localist representations can account for our finding of both cumulative frequency and frequency trajectory effects in lexical decision. For instance, in Coltheart et al.'s (2001) dual-route cascaded (DRC) model, the frequency of the words is encoded at the level of the orthographic units within the lexical route, so that the activation of high-frequency words rises more quickly than the activation of low-frequency words. Lexical decisions are performed upon decision criteria implemented in the model. The DRC model includes semantic pathways between orthographic and phonological word units, but as the semantic part of the model has not been fully implemented, it remains to be seen how the model might be altered in a way to simulate AoA effects in the lexical decision task. In our view, Plaut's (1997) computational work thus far promises to provide the most parsimonious account of age-limited learning effects in visual lexical decision.

Concerning spoken and written naming, our finding of an effect of cumulative frequency is clearly at odds with the results of Bonin et al. (2001b), Bonin et al. (2002) and Chalard et al. (2003) who reported no reliable frequency effects in factorial and multiple regression studies when rated AoA or objective AoA were taken into account. However, these studies did not consider cumulative frequency or frequency trajectory (as they were conducted before the MANULEX child frequency norms were available and before the notion of frequency trajectory was introduced). Thus, we are forced to reconsider the claim made by Chalard et al. (2003) that AoA is the most important factor to take into account in modeling picture naming. On the contrary, our reanalyses suggest that both cumulative frequency and frequency trajectory are important factors, and so theories of object naming must provide accounts for the effects of both variables. Levelt et al.'s (1999) influential theory of lexical access in speech has focused on word frequency but not on AoA effects. These authors have simply assumed that both effects can be modelled in the same way, but have presented no convincing argument for why or how. Other authors have located word frequency effects in the links relating semantic and phonological codes and AoA effects to the phonological representations themselves (Barry et al., 1997), based on the finding that rated AoA and word frequency interact such that the frequency effect was larger for late-acquired than early acquired words.[5] If the phonological representations contacted during spoken picture naming and word reading are the same, and age-limited learning effects are located at the phonological representations themselves, then it is very difficult to account for our current findings that age-limited learning effects are found in spoken naming but not in word reading. The modeling work of Ellis and Lambon Ralph (2000) and Zevin and Seidenberg (2002) suggests that both effects can be seen as emerging from a common mechanism, namely the encoding in the links relating semantic, orthographic and phonological representations, although future work is required to address this issue in greater depth.

The dominant view of spelling to dictation is that adults can use two processing pathways to derive orthography from spoken input, as in versions of the dual-route model (e.g., Barry & Seymour, 1988; Rapp, Epstein, & Tainturier, 2002; Tainturier & Rapp, 2000). A lexical route retrieves spellings of words from a lexical store and an assembled route converts sound units to spelling units sub-lexically. Dual-route models have been supported primarily by evidence from the impaired spelling performance of neuropsychological patients with varieties of acquired dysgraphia (Barry, 1994). There have been only a few studies of written spelling to dictation production latencies in normals but one such study by Bonin and Méot (2002) reported that spelling latencies were affected by rated AoA and adult word frequency. However, our re-analyses of their data showed that cumulative frequency, but not frequency trajectory, affected written spelling times, and these results, unlike those originally reported by Bonin and Méot', therefore present no major challenge to either dual-route or connectionist (e.g., Brown & Loosemore, 1994; Houghton, Glasspool, & Shallice, 1994) models of spelling to dictation. The observation that frequency trajectory has no reliable influence in spelling to dictation is clearly in accordance with the view advocated by Zevin and Seidenberg (2002). Since spelling to dictation, like word reading, involves quasi-regular mapping relationships (although, in French, these are more inconsistent for spelling than they are for reading), what is learned about the spelling of one word can carry over to other words. Therefore, as in word reading, there is no need to memorize individual patterns in learning the spelling of most familiar words. Nevertheless, semantics may play a role in spelling when these representations are particularly useful to disambiguate the spelling of heterographic homophones (such as *rain*, *rein*, and *reign*). It remains to be seen whether AoA effects would be found in spelling such words.

In conclusion, the strength of our study lies in our examination of the contribution of frequency trajectory and cumulative frequency to word reading and other lexical tasks. We have shown that cumulative frequency affects performance in all these tasks. It has been argued that a better test of whether there are real age-limited

[5] This interaction was not replicated in the present study using cumulative frequency and frequency trajectory.

learning contributions to lexical processing would be to examine the effects of frequency trajectory rather than currently used measures of AoA. We have shown that frequency trajectory affects performance in spoken and written picture naming and in the lexical decision task, but that it has no effect on oral reading or written spelling latencies. These results are important in that they show that there are genuine age-limited learning effects in tasks that involve arbitrary mappings between different representations.

Reference notes

1. Zevin, J. D., & Seidenberg, M. S. (2002). Frequency trajectory and the circularity problem in defining, modeling and testing AoA effects. Paper presented at the 19th British Psychology Society Cognitive Section, University of Kent, Canterbury, UK.
2. Ellis, A. W. (2002). Approaches to modeling age of acquisition. Paper presented at the 19th British Psychology Society Cognitive Section, University of Kent, Canterbury, UK.

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Appendix. Mean naming latencies (NL in ms) for the items used in the multiple regression analysis of word naming

Stimulus word	English translation	NL
Abeille	Bee	495
Accordéon	Accordion	521
Aigle	Eagle	493
Ampoule	Light bulb	496
Ananas	Pineapple	487
Ancre	Anchor	484
Ane	Donkey	483
Araignée	Spider	502
Arbre	Tree	479
Arrosoir	Watering can	514
Autruche	Ostrich	553
Avion	Airplane	469
Bague	Ring	482
Balai	Broom	489
Balançoire	Swing	524
Ballon	Balloon	479
Banane	Banana	493
Boîte	Box	479
Bol	Bowl	500
Botte	Boot	475
Bougie	Candle	499

Appendix *(continued)*

Stimulus word	English translation	NL
Bouteille	Bottle	498
Bouton	Button	511
Bras	Arm	489
Brosse	Brush	484
Bureau	Desk	491
Cadenas	Lock	556
Camion	Truck	509
Canapé	Couch	516
Canard	Duck	514
Canon	Cannon	515
Carotte	Carrot	506
Casquette	Cap	531
Casserole	Pot	535
Ceinture	Belt	553
Cerf	Deer	588
Cerise	Cherry	563
Chaîne	Chain	576
Chaise	Chair	550
Chameau	Camel	571
Champignon	Mushroom	530
Chapeau	Hat	535
Chat	Chair	517
Chaussette	Sock	564
Chaussure	Shoe	550
Chemise	Shirt	556
Chenille	Caterpillar	565
Cheval	Horse	539
Chèvre	Goat	571
Chien	Dog	568
Cigare	Cigar	643
Cigarette	Cigarette	629
Cintre	Hanger	560
Ciseau	Scissors	642
Citron	Lemon	623
Citrouille	Pumpkin	634
Cloche	Bell	529
Clou	Nail	511
Clown	Clown	541
Cochon	Pig	511
Coeur	Heart	512
Collier	Necklace	521
Coq	Rooster	511
Couronne	Crown	563
Couteau	Knife	536
Cravate	Tie	516
Crayon	Pencil	533
Crocodile	Crocodile	589
Cuillère	Spoon	575
Cygne	Swan	622
Doigt	Finger	495
Drapeau	Flag	581
Echelle	Ladder	494
Ecureuil	Squirrel	496
Eglise	Church	475
Eléphant	Elephant	490
Enveloppe	Envelope	507
Escargot	Snail	516
Etoile	Star	466

Appendix *(continued)*

Stimulus word	English translation	NL
Fenêtre	Window	550
Feu	Traffic light	553
Feuille	Leaf	551
Flèche	Arrow	561
Fleur	Flower	544
Fourchette	Fork	587
Fourmi	Ant	566
Fraise	Strawberry	560
Gant	Glove	484
Gâteau	Cake	493
Girafe	Giraffe	544
Gorille	Gorilla	531
Grenouille	Frog	520
Guitare	Guitar	522
Hache	Axe	511
Hélicoptère	Helicopter	559
Hibou	Owl	502
Hippocampe	Sea horse	640
Horloge	Clock	492
Interrupteur	Light switch	624
Jambe	Leg	509
Jupe	Skirt	553
Kangourou	Kangaroo	557
Lampe	Lamp	494
Landau	Baby carriage	538
Lapin	Rabbit	486
Lèvres	Lips	479
Lion	Lion	479
Lit	Bed	491
Livre	Book	465
Luge	Sled	484
Lune	Moon	484
Lunettes	Glasses	508
Main	Hand	454
Maïs	Corn	500
Maison	House	468
Manteau	Coat	480
Marteau	Hammer	484
Montagne	Mountain	493
Montre	Watch	459
Moto	Motorcycle	460
Mouche	Fly	459
Moufle	Mitten	476
Moulin	Windmill	480
Mouton	Sheep	470
Nez	Nose	457
Noeud	Bow	488
Oeil	Eye	509
Oiseau	Bird	485
Orange	Orange	480
Oreille	Ear	477
Ours	Bear	491
Panier	Basket	497
Pantalon	Pants	507
Papillon	Butterfly	484
Parapluie	Umbrella	537

Appendix *(continued)*

Stimulus word	English translation	NL
Peigne	Comb	529
Phoque	Seal	613
Piano	Piano	535
Pied	Foot	538
Pince	Pliers	494
Pinceau	Paintbrush	516
Pingouin	Penguin	574
Pipe	Pipe	521
Poêle	Frying pan	554
Poire	Pear	504
Poisson	Fish	500
Pomme	Apple	507
Porte	Door	502
Poubelle	Garbage can	525
Pouce	Thumb	526
Poule	Chicken	503
Prise	Plug	517
Puits	Well	552
Raisin	Grape	514
Règle	Ruler	517
Renard	Fox	507
Rhinocéros	Rhinoceros	647
Robe	Dress	517
Roue	Wheel	507
Sauterelle	Grasshopper	610
Scie	Saw	624
Serpent	Snake	525
Sifflet	Whistle	628
Singe	Monkey	548
Soleil	Sun	537
Souris	Mouse	559
Stylo	Pen	620
Table	Table	520
Tabouret	Stool	542
Tambour	Drum	520
Tasse	Cup	512
Téléphone	Telephone	527
Tigre	Tiger	595
Tomate	Tomato	509
Tonneau	Barrel	552
Tortue	Turtle	484
Toupie	Top	516
Tournevis	Screwdriver	551
Train	Train	526
Trompette	Trumpet	541
Vache	Cow	490
Valise	Suitcase	484
Vase	Vase	481
Vélo	Bicycle	494
Verre	Glass	492
Veste	Jacket	488
Violon	Violin	530
Vis	Screw	493
Voiture	Car	486
Zèbre	Zebra	524

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