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Brief article

# Age-of-acquisition effects in visual word recognition: evidence from expert vocabularies

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**Abstract**

Three experiments assessed the contributions of age-of-acquisition (AoA) and frequency to visual word recognition. Three databases were created from electronic journals in chemistry, psychology and geology in order to identify technical words that are extremely frequent in each discipline but acquired late in life. In Experiment 1, psychologists and chemists showed an advantage in lexical decision for late-acquired/high-frequency words (e.g. a psychologist responding to *cognition*) over late-acquired/low-frequency words (e.g. a chemist responding to *cognition*), revealing a frequency effect when words are perfectly matched. However, contrary to theories that exclude AoA as a factor, performance was similar for the late-acquired/high-frequency and early-acquired/low-frequency words (e.g. *dragon*) even though their cumulative frequencies differed by more than an order of magnitude. This last finding was replicated with geologists using geology words matched with early-acquired words in terms of concreteness (Experiment 2). Most interestingly, Experiment 3 yielded the same pattern of results in naming while controlling for imageability, a finding that is particularly problematic for parallel distributed processing models of reading.


*Keywords:* Age-of-acquisition; Visual word recognition; Expert vocabulary; Cumulative Frequency; Lexical decision; Word naming; Connectionist models

## 1. Introduction

There is controversy concerning the relative importance of frequency and age-of-acquisition (AoA) in predicting performance in various visual word recognition tasks,

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including naming and lexical decision tasks (LDT). Some studies suggest that AoA makes little or no independent contribution to performance (e.g. Lewis, 1999a,b; Zevin & Seidenberg, 2002). Others suggest that both AoA and frequency are potent factors (e.g. Ellis & Morrison, 1998; Gerhand & Barry, 1998, 1999a,b; Moore, Valentine, & Turner, 1999), and some even provide evidence that AoA is the only factor (e.g. Brown & Watson, 1987; Gilhooly, 1984; Gilhooly & Gilhooly, 1979; Morrison & Ellis, 1995; Morrison, Ellis, & Quinlan, 1992; Vitkovitch & Tyrrell, 1995). There is similar confusion regarding the role of word frequency and AoA in constraining performance in connectionist models of word identification. For example, Ellis and Lambon Ralph (2000) have argued that both frequency and AoA effects are intrinsic to these models when trained with interleaved learning, while Zevin and Seidenberg (2002) argue that AoA effects are not present in more realistic models that include orthotactic and phonotactic constraints.

One of the challenges in resolving the controversy in the behavioral studies is the high correlation between frequency and AoA (e.g. $r = -0.68$ in Carroll & White, 1973). They also both correlate to other factors such as word length, neighborhood, imageability, concreteness and familiarity (Zevin & Seidenberg, 2002). This strong intercorrelation makes it difficult to isolate the contribution of AoA per se. It also narrows the range of words that can be used in factorial designs, with early-acquired/low-frequency words and late-acquired/high-frequency words difficult to find.

Another problem noted by Zevin and Seidenberg (2002) is that many of the studies reporting AoA effects in LDT (e.g. Gerhand & Barry, 1999a; Morrison & Ellis, 1995, 2000; Turner, Valentine, & Ellis, 1998) and word naming (e.g. Gerhand & Barry, 1999a; Monaghan & Ellis, 2002; Morrison & Ellis, 1995, 2000) relied on the Kucera and Francis (1967) norms in order to assess frequency. Because this database is based on only one million tokens, it suffers from potentially large measurement errors, especially for low-frequency words. When the authors re-estimated frequencies using larger databases such as CELEX (Baayen, Piepenbrock, & Van Rijn, 1993) and the Educator's Word Frequency Guide (WFG; Zeno, Ivens, Millard, & Duvvuri, 1995), they found that words in the early-acquired condition were often higher in frequency than late-acquired items, suggesting that their advantage was the product of frequency rather than AoA.

Even when better frequency norms are used, there remains a difficulty. When contrasting the role of frequency and AoA, frequency estimates should presumably measure the number of times a person has read a word over his or her life (so-called cumulative frequency), yet these databases used only provide an estimate of how often adult readers encounter words. This is a subtle but important distinction. Consider the words *bubble* and *organic* that have equal frequencies in the CELEX norms[1] ($F = 15$) but have different AoAs (4.26 and 12.92 years, respectively). If RTs to *bubble* were shorter it might appear to reflect an AoA effect given that the items were matched on CELEX frequency. However, given that *bubble* is encountered earlier in life, its cumulative frequency is higher than *organic*, in which case the RT difference might reflect cumulative frequency.

Of course it is not possible to eliminate all measurement errors associated with frequency corpora or obtain an exact measure of cumulative frequency for each

[1] All CELEX and Expert Frequencies are given in counts per million through the paper. All CELEX frequencies are taken from the ECT database.

participant. Nevertheless, a strong test of AoA vs. cumulative frequency could be made if the estimated separation between conditions in a factorial design was large enough to render the inevitable measurement errors irrelevant. In order to achieve this, we created *Expert Frequency Databases* with words acquired late in life but that have a very high frequency for a specific population. Using these databases along with CELEX we were able to select words with differences in AoA and frequency that are much larger than past studies (see Appendix A). If, as proposed by Zevin and Seidenberg (2002), cumulative frequency but not AoA plays a role in visual word recognition, one would expect late-acquired words with overwhelmingly larger frequency counts to have a substantial advantage over early-acquired words with a much lower cumulative frequency in both LDT and naming.

## 2. Experiment 1: lexical decision with chemistry and psychology words

### *2.1. Method*

#### *2.1.1. Participants*

Twelve PhDs in cognitive psychology and 12 in chemistry were tested. All were British English native speakers (see Table 1).

#### *2.1.2. Design and materials*

A *Cognitive Psychology Expert Frequency Database* and a *Chemistry Expert Frequency Database* of approximately 3 million tokens each were created using

Table 1
Average participant characteristics used in calculating approximate cumulative frequency of words

| | Age (years) | Years with PhD | Academic reading[a] | Estimated relative cumulative frequency[b] | |
|---|---|---|---|---|---|
| | | | | Late/HighF divided by Early/LowF | Late/HighF divided by Early/HighF |
| Psychologists | 41.4 (31–68) | 13.6 (2–29) | 52% | 15.3 | 0.9 |
| Chemists | 36.7 (27–45) | 10.2 (2–19) | 47% | 20.3 | 1.2 |
| Geologists (Experiment 2) | 41.7 (27–59) | 13.6 (2–31) | 52% | 13.3 | 0.2 |
| Geologists (Experiment 3) | 44.1 (31–64) | 14.5 (3–32) | 63% | 26.3 | 0.2 |

[a] “Academic reading” is a self-estimate of how much participants read in their own area of expertise as a proportion of all their reading.

[b] Estimated relative cumulative frequency: a rough estimate of the proportion of cumulative use of a word given in tokens per million. The estimate for both early conditions was obtained by multiplying the average CELEX frequency of these words by the years of use (that is, the age of the participants minus the AoA of the words). For late words, the values from the Expert Frequency Databases were multiplied by the PhD years of the participants and by the proportion of academic reading (usage of these words before PhD was not included, although if taken into account this would only strengthen the point illustrated here).

recent electronic editions of three journals from each discipline.[2] The "expert frequency" estimate for words in each discipline was the average of the frequency (in counts per million) for each word from all three journals. A word was classified as "high expert frequency" if it had a frequency of more than 100 in each of the three journals and it had a frequency of 15 or less on the *Expert Frequency Database* of the other discipline *and* in CELEX. Conversely, a word was classified as low-frequency if its expert *and* CELEX frequencies were 15 or less. AoA estimates (in years) were provided by 12 psychology and 12 chemistry graduate students, with all items randomly intermixed. Participants were asked to indicate the age at which they would have understood the spoken form of each word. A word was classified as "late-acquired" if its rating was above 10 years and "early-acquired" if it was below 6 years.

Four lists of 16 words each were constructed: (1) psychology terms: late AoA and high psychology expert frequency (e.g. *cognition*); (2) chemistry terms: late AoA and high chemistry expert frequency (e.g. *electron*); (3) Early/LowF words: low CELEX frequency and early AoA (e.g. *dragon*); (4) Early/HighF words: high CELEX frequency and early AoA (e.g. *smile*). The words in conditions 1 and 2 served as Late/HighF items when read by the relevant expert (e.g. psychologist reading *cognition*), and Late/LowF items otherwise (e.g. chemist reading *cognition*). Words in each group were controlled for length and there were no significant differences in neighborhood size (all $F$ values $<1.26$, $P$ values $>0.27$).[3] We also present frequency counts from the Educator's WFG (Zeno et al., 1995). See Appendix A for details.

We estimated that the cumulative frequency for Late/HighF words was at least 15 times larger than Early/LowF words (see Table 1). Even if this calculation were overestimated by a factor of 10, words classified as late-acquired would still have a larger cumulative frequency than early words.

A set of pronounceable non-words was constructed by changing a letter from additional words taken from the Expert Frequency and CELEX Databases. Non-words and words were matched in length, and there were no significant differences in their length-sensitive token bigram frequency (based on CELEX; Davis, 2004).

### 2.1.3. Procedure

The LDT was self-paced and items were presented in random order. A non-overlapping set of 16 practice items was included. Stimuli were presented in lower case Courier-New font, 10-point size, with black letters over white background. The experiment was run using DMDX (Forster & Forster, 2003).

[2] Journals used for the *Experimental Psychology Expert Frequency Database*: Cognition, 846,213 tokens; Cognitive Psychology, 1,574,683 tokens; Quarterly Journal of Experimental Psychology, 772,898 tokens. For the *Chemistry Expert Frequency Database*: Chemistry, 1,151,593 tokens; Chemical Society Reviews, 553,057 tokens; New Journal of Chemistry, 1,294,642 tokens.

[3] Experiment 1. Mean neighborhood values: Psychology = 1.6, Chemistry = 0.7, Early/LowF = 1.8, Early/HighF = 1.3. Through this study, "neighborhood" refers to "Coltheart's N" (Coltheart, Davelaar, Jonasson, & Besner, 1977).

### 2.2. Results

Only the word data were analyzed, and the results are shown in Appendix A. Scores more than 2.5 SD from the mean were removed (1.1%). The word *lexical* was excluded because its error rate for chemists was more than 20% and more than 2.5 SD above the mean. The word *chemistry* was also removed because its rated AoA (8.53 years) was too low for its assigned condition. Analyses were carried out both by subjects ($F_1$) and by items ($F_2$).

Collapsing across groups, Late/HighF words (e.g. a chemist's response to *carbon*) have an advantage over Late/LowF words (e.g. a psychologist's response to *carbon*) both for speed (581 vs. 653 ms, $F_1(1,23) = 42.02$, $P < 0.01$; $F_2(1,59) = 23.76$, $P < 0.01$) and errors (3.8% vs. 13.9%, $F_1(1,23) = 16.67$, $P < 0.01$; $F_2(1,59) = 12.04$, $P < 0.01$). These results provide strong evidence for a frequency effect for late-acquired words since high- and low-frequency words were matched on all other possible variables (they were the same words), and only the frequency of exposure to the words was varied (by manipulating the population). This is consistent with the results obtained by Gardner, Rothkopf, Lapan, and Lafferty (1987) who observed that nurses responded faster to medical terms than lawyers and engineers.

With regards to AoA, Late/HighF words (e.g. a chemist's response to *carbon*) did not have a significant advantage over Early/LowF words (e.g. a chemist's response to *dragon*) in RTs (581 vs. 580 ms, $F_1(1,23) < 1$; $F_2(1,61) < 1$) nor errors (3.7% vs. 4.7%, $F_1(1,23) < 1$; $F_2(1,61) < 1$). These results suggest that AoA is also a significant factor in word recognition, since a pure frequency account would predict much better performance for Late/HighF words given the extreme cumulative frequency differences between conditions. The lack of advantage for Late/HighF over Early/LowF words cannot be attributed to a floor effect since performance was better for Early/HighF (532 ms, $F_1(1,23) = 55.57$, $P < 0.01$; $F_2(1,61) = 21.02$, $P < 0.01$; 2.4% errors, $F_1(1,23) < 1$; $F_2(1,61) = 1.38$, $P = 0.24$). AoA effects are also supported by the finding that RTs were much reduced for the Early/HighF compared to Late/HighF items (533 vs. 582 ms, $F_1(1,23) = 55.57$, $P < 0.01$; $F_2(1,61) = 21.02$, $P < 0.01$; errors: 2.3% vs. 3.8%, $F_1(1,30) = 1.67$, $P = 0.21$; $F_2(1,61) = 1.38$, $P = 0.24$) despite items having comparable cumulative frequency counts.

A possible criticism of the AoA findings is that items were not matched for concreteness or imageability, factors that may affect performance in the LDT (e.g. Kroll & Merves, 1986). Similarly, we did not match items on bigram frequency.[4] We address both of these concerns in Experiments 2 and 3.

[4] Post-hoc concreteness ratings (cf. Spreen & Schulz, 1966, p. 460) by 20 psychology students showed large differences for the three critical conditions, with Psychology Words rated as the most abstract (2.86/7), followed by Chemistry Words (4.30/7) and Early/LowF words (6.24/7). Bigram frequency means (Davis, 2004) by Tokens: Psychology = 871.3, Chemistry = 534.6, Early/LowF = 710.2, Early/HighF = 884.7; by Types: Psychology = 83.6, Chemistry = 37.6, Early/LowF = 66.2, Early/HighF = 54.9.

## 3. Experiment 2: lexical decision with geology words

### 3.1. Method

#### 3.1.1. Participants

Twenty PhDs in geology were tested (see Table 1).

#### 3.1.2. Design, materials and procedure

A *Geology Expert Frequency Database* of approximately 3.8 million tokens was created using three geology journals.[5]

Three conditions of 16 words each were included: (1) Late/HighF: late AoA and high geology expert frequency (e.g. *basalt*); (2) Early/LowF: low CELEX frequency and early AoA (e.g. *dragon*); (3) Early/HighF: high CELEX frequency and early AoA (e.g. *water*). Words on the three lists were closely matched for length and concreteness and there were no significant differences in neighborhood ($F$ values $<2.1$, $P$ values $>0.16$). Geology and Early/Low words were also controlled for length-sensitive positional bigram and trigram frequencies (both by tokens and by types; $t$ values $<1.2$, $P$ values $>0.2$; based on CELEX; Davis, 2004).[6] Twenty geology graduate students provided estimates for AoA (in years) and concreteness (on a seven-point scale) (see Appendix A). The instructions were identical to those used by Spreen and Schulz (1966, p. 460). An additional set of 16 items with low concreteness (e.g. *luck*) was randomly intermixed with the critical items in order to encourage participants to use the entire range of the scale. Ratings were obtained from geology graduate students because semantic attributes of specialized words are likely to differ for experts. The cumulative frequency for the Late/HighF (geology) words was estimated to be more than 13 times larger than for Early/LowF words (see Table 1).

The characteristics of the non-words and the testing procedures used were similar to those in Experiment 1.

### 3.2. Results

The same criteria for detecting outliers as in Experiment 1 were applied both for individual RTs (2.8% were dropped) and errors (*rhyme* was eliminated). Appendix B shows the results. There was no advantage for Late/HighF (e.g. *zircon*) over Early/LowF words (e.g. *dragon*) for speed (553 vs. 564 ms, $F_1(1,19) = 1.30$, $P = 0.27$; $F_2(1,29) < 1$) nor errors (3.1% vs. 5.7%, $F_1(1,19) = 1.63$, $P = 0.22$; $F_2(1,29) = 1.73$, $P = 0.20$).[7]

[5] Journals used for the *Geology Expert Frequency Database*: Geology, 566,818 tokens; GSA Bulletin, 1,800,352 tokens; Journal of Geology, 1,477,179 tokens.

[6] Experiment 2. Mean neighborhood: Geology = 0.7, Early/LowF = 1.8, Early/HighF = 2.0; Bigram Token Frequencies: Geology = 800.0, Early/LowF = 830.7; Bigram Type Frequencies: Geology = 49.1, Early/LowF = 48.6; Trigram Token Frequencies: Geology = 152.4, Early/LowF = 94.0; Trigram Type Frequencies: Geology = 9.0, Early/LowF = 9.2.

[7] It is interesting to note here that a large portion of the difference in error rates between these two conditions comes from the word *daffodil* (20% error), which has an unusual spelling. If this word is eliminated from the analyses the numerical differences become smaller still, both for error rates (3.1% vs. 4.6% error, $F_2(1,28) = 0.78$, $P = 0.38$) and RTs (553 vs. 558 ms, $F_2(1,28) = 0.27$, $P = 0.61$).

Performance for Early/HighF words was better than the other conditions (530 ms, $F_1(1, 19) = 7.01$, $P < 0.05$; $F_2(1, 30) = 6.54$, $P < 0.05$; 1.9% errors, $F_1(1, 19) < 1$; $F_2(1, 30) = 1.11$, $P = 0.30$) ruling out a floor effect. The important finding is not that performance for the Early/LowF and Late/HighF items was equivalent, but rather that performance for the Late/HighF items was not much better given their frequency counts. Indeed, based on the cumulative frequency hypothesis, RTs and error rates for the Late/HighF items should have been more similar to the Early/HighF items, which is not the case.

It should be noted that Zevin and Seidenberg's (2002) simulations concerned word naming and not lexical decision (although they made claims about both), and accordingly, it is important to assess AoA and frequency effects in the naming task as well. Experiment 3 was designed to test if an AoA effect would still be present in a word naming task while controlling tightly for imageability.

## 4. Experiment 3: word naming with geology words

### 4.1. Method

#### 4.1.1. Participants

Fifteen PhDs in geology were tested (see Table 1).

#### 4.1.2. Design and materials

A set of 48 words were classified into the same three conditions as in Experiment 2, but this time they were matched for full onset or initial vowel, as well as length and neighborhood (all $F$ values $< 1$). Geology and Early/LowF words were matched in length-sensitive positional bigram and trigram frequencies (both by tokens and by types; $t$ values $< 1.2$, $P$ values $> 0.2$).[8] Items in these two conditions were also tightly controlled for AoA and imageability, with ratings coming from 12 geology graduate students (see Appendix C). Imageability scores were made on a seven-point scale and the instructions were identical to those in Paivio, Yuille, and Madigan (1968, p. 4). A total of 193 words were rated on the same session (37 geology words as well as 72 and 84 candidate early/low and early/high words, respectively). All items were randomly intermixed. The cumulative frequency of the 16 selected Late/HighF (geology) words was estimated to be 26 times larger than of the 16 Early/LowF words (see Table 1).

#### 4.1.3. Apparatus

The experiment was run on a portable computer using DMDX software. Responses were captured using a Sennheiser m@b40 headset microphone and recorded directly into the computer's hard drive.

[8] Experiment 3. Mean neighborhood: Geology = 1.8, Early/LowF = 2.8, Early/HighF = 2.2; Bigram Token Frequencies: Geology = 1063.2, Early/LowF = 915.3; Bigram Type Frequencies: Geology = 67.4, Early/LowF = 45.7; Trigram Token Frequencies: Geology = 279.2, Early/LowF = 162.1; Trigram Type Frequencies: Geology = 19.6, Early/LowF = 8.2.

#### 4.1.4. Procedure

Participants initiated each trial by pressing the space bar; a fixation cross then appeared in the center of the screen for 500 ms and was replaced by a target word. Participants named words as quickly and accurately as possible. Sixteen practice trials preceded the experiment and critical items were randomized for each participant. The visual characteristics of the stimuli were identical to the previous experiments.

### 4.2. Results

Non-speech signals (e.g. lip-pops, clicks and external noises) were manually removed from the sound files prior to analysis. There were too few mispronounced items (0.6%) to allow an error analysis. Individual responses more than 2.5 SD from the mean were removed (four from geology, two from Early/Low, four from Early/High). Reaction times were calculated using Runword (Kello & Kawamoto, 1998). Appendix C presents the results. Once again there was no significant advantage for Late/HighF (geology) over Early/LowF words (473 vs. 478 ms, $F_1(1,14) = 1.01$, $P = 0.33$; $F_2(1,30) < 1$), and this is not due to a floor effect (Early/HighF = 458 ms, $F_1(1,14) = 15.96$, $P < 0.01$; $F_2(1,30) = 9.16$, $P < 0.01$).

## 5. General discussion

The present experiments provide evidence for the independent contribution of AoA and cumulative frequency in word processing tasks when the usual confound between these factors is removed. This evidence comes from the similar RTs obtained for Late/HighF (expert vocabulary) and Early/LowF words in the lexical decision (Experiments 1 and 2) and naming (Experiment 3) tasks despite the fact that the cumulative frequency of the HighF words was over an order of magnitude greater. The cumulative frequency account, by contrast, would predict a large advantage for the Late/HighF items. It is important to note that our conclusions are not based on null effects, and we would not alter our conclusion even if the small differences in performance between the critical conditions were significant. Critically, the current results were obtained when the various criticisms of past studies raised by Zevin and Seidenberg (2002) do not apply. A second finding is that Late/HighF words (e.g. a chemist reading *carbon*) were responded to more quickly than Late/LowF items (e.g. a psychologist reading *carbon*) when items were matched on all possible variables (they were the same words) which shows that frequency also plays a role in LDT performance (Experiment 1).

The AoA findings pose a serious challenge to standard parallel distributed processing (PDP) accounts of word naming. According to Zevin and Seidenberg (2002), the reason the PDP model (and humans) fails to show AoA effects in word naming (and lexical decision) is that there is a systematic relation between orthography and phonology, such that similar input patterns (e.g. the orthographic forms *prince* and *print*) map onto similar output patterns (e.g. the phonological forms /prIns/ and /prInt/, respectively). Under these conditions, early learning (*prince* → /prIns/) contributes to late learning (*print* → /prInt/), eliminating any AoA differences. Although this analysis appears correct in the case of their model, it mischaracterizes human behavior given that strong AoA effects are obtained in naming and lexical decision tasks.

Zevin and Seidenberg (2002) also note that there is some behavioral evidence that AoA effects are larger in tasks involving arbitrary input–output mappings (e.g. picture naming) compared to systematic mappings (e.g. word naming), consistent with PDP accounts of AoA (also see Monaghan and Ellis, 2002). However, it should be noted that this prediction is not unique to PDP models, and indeed, the dual-route model of reading makes the same prediction. The reasoning is straightforward: AoA is a lexical variable, and accordingly, AoA effects will be reduced to the extent that sub-lexical grapheme–phoneme correspondences contribute to performance. This is the case in word but not picture naming in the dual-route framework. What PDP models of word naming do uniquely predict is that AoA effects are eliminated when the input–output mappings are systematic, and this prediction is falsified in the present studies.

Based on these findings, we would suggest that AoA (and frequency) effects may reflect the structure of lexical–orthographic and lexical–phonological representations themselves. That is, both Early and HighF words may have "stronger" lexical representations that are more easily accessed, just as Morton (1979), McClelland and Rumelhart (1981), and Davis (1999) have argued in the case of frequency. On this latter approach, AoA effects should be observed even under conditions in which input–output mappings are systematic. But clearly future work is required in order to determine whether networks that learn lexical codes can account for the independent contribution of AoA and frequency.

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**Appendix A**

Word properties and performance data for items in Experiment 1

| Word | Psyc F | Chem F | Celex F | WFG | AoA | Psyc RT | Psyc %Error | Chem RT | Chem %Error |
|---|---|---|---|---|---|---|---|---|---|
| *Psychology* | | | | | | | | | |
| Auditory | 279 | 0 | 1 | 4 | 14.2 | 584 | 8.3 | 706 | 16.7 |
| Bias | 310 | 14 | 10 | 4 | 12.8 | 599 | 0.0 | 615 | 8.3 |
| Cognition | 1340 | 0 | 0 | 0 | 16.5 | 523 | 0.0 | 762 | 25.0 |
| Cue | 317 | 0 | 6 | 1 | 10.7 | 538 | 8.3 | 657 | 8.3 |
| Encoding | 300 | 3 | 0 | 0 | 14.9 | 515 | 16.7 | 640 | 16.7 |
| Explicit | 274 | 4 | 10 | 2 | 13.6 | 557 | 0.0 | 660 | 8.3 |
| Inference | 223 | 0 | 4 | 1 | 15.0 | 619 | 8.3 | 659 | 8.3 |
| Lexical* | 419 | 0 | 1 | 0 | 17.5 | 589 | 25 | 770 | 66.7 |
| Participant | 184 | 0 | 3 | 2 | 10.9 | 563 | 0.0 | 615 | 0.0 |
| Phonology | 168 | 0 | 0 | 0 | 17.4 | 564 | 8.3 | 726 | 41.7 |
| Priming | 558 | 0 | 0 | 1 | 16.3 | 585 | 16.7 | 668 | 16.7 |
| Rating | 126 | 0 | 3 | 7 | 10.4 | 609 | 8.3 | 596 | 8.3 |
| Retrieval | 255 | 3 | 1 | 1 | 12.0 | 604 | 8.3 | 691 | 16.7 |
| Semantic | 515 | 0 | 2 | 1 | 17.4 | 587 | 0.0 | 795 | 25.0 |
| Serial | 285 | 0 | 4 | 1 | 11.7 | 543 | 0.0 | 620 | 0.0 |
| Stimulus | 818 | 4 | 11 | 13 | 13.2 | 539 | 0.0 | 640 | 25.0 |
| MEAN | 398.1 | 2.0 | 3.6 | 2.4 | 14.0 | 568.5 | 5.6 | 670.1 | 15.0 |
| *Chemistry* | | | | | | | | | |
| Aqueous | 0 | 481 | 0 | 1 | 14.2 | 850 | 41.7 | 588 | 0.0 |
| Carbon | 2 | 565 | 14 | 76 | 11.3 | 580 | 0.0 | 525 | 0.0 |
| Catalyst | 0 | 418 | 2 | 2 | 14.0 | 612 | 0.0 | 531 | 0.0 |
| Chemistry* | 5 | 1277 | 13 | 17 | 8.5 | 524 | 0.0 | 561 | 8.3 |
| Conformation | 0 | 284 | 0 | 0 | 14.0 | 653 | 0.0 | 725 | 0.0 |
| Electron | 0 | 937 | 6 | 18 | 12.7 | 701 | 16.7 | 582 | 8.3 |
| Ether | 0 | 327 | 1 | 2 | 14.5 | 687 | 58.3 | 637 | 0.0 |
| Hydrogen | 0 | 1015 | 13 | 33 | 11.3 | 533 | 0.0 | 563 | 0.0 |
| Ion | 9 | 658 | 2 | 3 | 13.6 | 621 | 16.7 | 624 | 0.0 |
| Molecular | 2 | 1030 | 3 | 4 | 13.3 | 647 | 0.0 | 536 | 8.3 |
| Nitrogen | 0 | 372 | 8 | 17 | 11.6 | 632 | 8.3 | 622 | 0.0 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Organic | 0 | 895 | 15 | 22 | 12.9 | 577 | 8.3 | 635 | 0.0 |
| Silica | 0 | 227 | 1 | 1 | 15.5 | 709 | 41.7 | 660 | 8.3 |
| Solvent | 0 | 675 | 2 | 6 | 12.7 | 569 | 0.0 | 593 | 0.0 |
| Spectrum | 10 | 544 | 8 | 11 | 11.5 | 600 | 0.0 | 550 | 0.0 |
| Synthesis | 8 | 1165 | 4 | 4 | 14.3 | 576 | 0.0 | 533 | 0.0 |
| MEAN | 2.3 | 679.5 | 5.9 | 13.4 | 13.2 | 636.5 | 12.8 | 593.7 | 1.7 |
| *Early/Low-frequency* | | | | | | | | | |
| Aeroplane | – | – | 8 | 0 | 4.6 | 588 | 0.0 | 692 | 0.0 |
| Alphabet | – | – | 3 | 15 | 4.1 | 528 | 8.3 | 605 | 0.0 |
| Banana | – | – | 4 | 5 | 4.1 | 531 | 0.0 | 546 | 0.0 |
| Bandage | – | – | 4 | 3 | 5.5 | 585 | 16.7 | 572 | 8.3 |
| Hop | – | – | 5 | 9 | 4.4 | 560 | 16.7 | 608 | 8.3 |
| Daffodil | – | – | 1 | 0 | 5.6 | 610 | 25.0 | 698 | 8.3 |
| Dentist | – | – | 6 | 5 | 4.9 | 553 | 0.0 | 541 | 8.3 |
| Caterpillar | – | – | 2 | 5 | 4.9 | 636 | 0.0 | 612 | 0.0 |
| Dragon | – | – | 8 | 18 | 4.8 | 573 | 0.0 | 584 | 0.0 |
| Pony | – | – | 8 | 18 | 4.8 | 527 | 0.0 | 666 | 0.0 |
| Princess | – | – | 12 | 21 | 4.1 | 523 | 16.7 | 550 | 0.0 |
| Knitting | – | – | 7 | 5 | 5.3 | 602 | 0.0 | 574 | 0.0 |
| Shepherd | – | – | 6 | 6 | 5.0 | 545 | 8.3 | 618 | 8.3 |
| Spider | – | – | 4 | 17 | 3.8 | 496 | 0.0 | 536 | 0.0 |
| Strawberry | – | – | 3 | 4 | 4.4 | 550 | 0.0 | 606 | 16.7 |
| Bubble | – | – | 4 | 6 | 4.3 | 578 | 0.0 | 572 | 0.0 |
| MEAN | | | 5.3 | 8.6 | 4.7 | 561.7 | 5.7 | 598.7 | 3.6 |
| *Early/High-frequency* | | | | | | | | | |
| Adult | – | – | 87 | 47 | 4.9 | 509 | 8.3 | 549 | 8.3 |
| Afraid | – | – | 112 | 96 | 5.0 | 565 | 0.0 | 556 | 0.0 |
| Beautiful | – | – | 116 | 148 | 4.9 | 474 | 0.0 | 569 | 0.0 |
| Beside | – | – | 90 | 87 | 6.0 | 555 | 8.3 | 574 | 0.0 |
| Daughter | – | – | 100 | 58 | 4.5 | 509 | 0.0 | 527 | 0.0 |
| Farmer | – | – | 31 | 46 | 4.4 | 492 | 0.0 | 523 | 8.3 |
| Flower | – | – | 28 | 40 | 3.5 | 498 | 0.0 | 562 | 16.7 |

(*continued on next page*)

Appendix A (*continued*)

| Word | Psyc F | Chem F | Celex F | WFG | AoA | Psyc RT | Psyc %Error | Chem RT | Chem %Error |
|---|---|---|---|---|---|---|---|---|---|
| Holiday | – | – | 58 | 14 | 4.2 | 465 | 8.3 | 543 | 0.0 |
| Kitchen | – | – | 106 | 104 | 3.8 | 496 | 0.0 | 567 | 8.3 |
| Mountain | – | – | 46 | 118 | 4.7 | 506 | 0.0 | 615 | 0.0 |
| Quickly | – | – | 150 | 207 | 4.7 | 514 | 0.0 | 553 | 0.0 |
| Sky | – | – | 77 | 146 | 3.3 | 503 | 0.0 | 527 | 0.0 |
| Smile | – | – | 93 | 60 | 3.5 | 492 | 0.0 | 557 | 0.0 |
| Soldier | – | – | 26 | 22 | 5.3 | 526 | 0.0 | 539 | 8.3 |
| Telephone | – | – | 101 | 72 | 4.3 | 528 | 0.0 | 555 | 0.0 |
| Television | – | – | 114 | 69 | 3.4 | 500 | 0.0 | 565 | 0.0 |
| MEAN | | | 83.5 | 83.4 | 4.4 | 508.2 | 1.6 | 555.0 | 3.1 |

Psyc F, frequency from the cognitive psychology expert frequency database; Chem F, frequency from the chemistry expert frequency database; Celex F, frequency from the CELEX database (Baayen et al., 1993); WFG, frequency from the Educator's Word Frequency Guide (Zeno et al., 1995); AoA = age-of-acquisition rating (in years); Psyc RT, reaction time from psychologists in ms; Psyc %Error, error rate for psychologists; Chem RT, reaction time from chemists in ms; Chem %Error, error rate for chemists. All frequencies are given in counts per million. *The RTs and error rates for these words are not included in the means (see details in Section 2.2).

**Appendix B**
Word properties and performance data for items in Experiment 2

| Word | Geo F | Celex F | WFG | AoA | Conc | RT | %Error |
|---|---|---|---|---|---|---|---|
| *Geology* | | | | | | | |
| Basalt | 316 | 0 | 1 | 10.8 | 6.1 | 539 | 0.0 |
| Carbonate | 551 | 0 | 2 | 13.3 | 5.7 | 569 | 0.0 |
| Erosion | 452 | 9 | 10 | 11.0 | 4.8 | 585 | 5.0 |
| Fluid | 400 | 14 | 24 | 10.1 | 5.3 | 556 | 0.0 |
| Garnet | 356 | 1 | 1 | 12.8 | 6.0 | 547 | 0.0 |
| Granite | 318 | 6 | 8 | 11.1 | 6.4 | 537 | 5.0 |
| Isotope | 677 | 0 | 0 | 13.8 | 4.8 | 573 | 0.0 |
| Magma | 291 | 0 | 1 | 12.2 | 6.3 | 532 | 0.0 |
| Mantle | 670 | 4 | 5 | 11.3 | 5.1 | 542 | 0.0 |
| Mineral | 552 | 6 | 26 | 10.7 | 6.0 | 544 | 5.0 |
| Plateau | 299 | 6 | 9 | 10.4 | 5.5 | 577 | 0.0 |
| Quartz | 569 | 1 | 5 | 10.3 | 6.2 | 524 | 5.0 |
| Sediment | 904 | 2 | 4 | 10.3 | 5.8 | 516 | 5.0 |
| Shear | 605 | 1 | 0 | 12.8 | 4.3 | 557 | 5.0 |
| Strata | 396 | 4 | 2 | 13.3 | 5.6 | 561 | 10.0 |
| Zircon | 512 | 0 | 0 | 14.0 | 5.9 | 592 | 10.0 |
| MEAN | 491.9 | 3.5 | 6.2 | 11.7 | 5.6 | 553.1 | 3.1 |
| *Early/Low-frequency* | | | | | | | |
| Aeroplane | – | 8 | 0 | 4.4 | 6.8 | 622 | 5.0 |
| Alphabet | – | 3 | 15 | 4.1 | 4.9 | 548 | 0.0 |
| Balloon | – | 3 | 28 | 4.3 | 4.9 | 549 | 0.0 |
| Bite | – | 17 | 21 | 4.3 | 4.6 | 601 | 10.0 |
| Bubble | – | 4 | 6 | 4.4 | 5.7 | 547 | 15.0 |
| Butterfly | – | 5 | 9 | 4.2 | 6.7 | 563 | 0.0 |
| Daffodil | – | 1 | 0 | 4.8 | 6.7 | 641 | 20.0 |
| Dragon | – | 8 | 18 | 4.4 | 4.3 | 536 | 15.0 |
| Fairy | – | 11 | 7 | 4.3 | 4.6 | 547 | 0.0 |
| Kitten | – | 4 | 13 | 3.8 | 6.6 | 545 | 0.0 |
| Pony | – | 8 | 18 | 4.3 | 6.2 | 536 | 5.0 |
| Princess | – | 12 | 21 | 4.6 | 5.5 | 562 | 0.0 |
| Puppy | – | 5 | 15 | 3.7 | 6.8 | 566 | 0.0 |
| Rhyme* | – | 2 | 4 | 4.8 | 3.7 | 596 | 35.0 |
| Spider | – | 4 | 17 | 3.8 | 6.8 | 508 | 10.0 |
| Umbrella | – | 11 | 9 | 4.8 | 6.7 | 583 | 5.0 |
| MEAN | | 6.6 | 12.6 | 4.3 | 5.7 | 563.5 | 5.7 |
| *Early/High-frequency* | | | | | | | |
| Between | – | 742 | 635 | 5.5 | 2.8 | 531 | 0.0 |
| Book | – | 275 | 290 | 3.3 | 6.5 | 523 | 0.0 |
| Children | – | 656 | 478 | 4.7 | 6.3 | 512 | 0.0 |
| Daughter | – | 100 | 58 | 4.0 | 5.9 | 521 | 5.0 |
| Friend | – | 172 | 173 | 4.0 | 4.8 | 511 | 10.0 |
| House | – | 559 | 645 | 3.7 | 6.7 | 496 | 0.0 |
| Kitchen | – | 106 | 104 | 3.9 | 6.6 | 589 | 0.0 |
| Morning | – | 302 | 301 | 3.9 | 4.8 | 566 | 5.0 |
| Party | – | 373 | 158 | 4.2 | 5.0 | 503 | 5.0 |
| People | – | 1465 | 2283 | 4.5 | 6.4 | 512 | 0.0 |

(*continued on next page*)

Appendix B (*continued*)

| Word | Geo F | Celex F | WFG | AoA | Conc | RT | %Error |
|---|---|---|---|---|---|---|---|
| Picture | – | 106 | 242 | 4.4 | 5.8 | 527 | 5.0 |
| School | – | 390 | 579 | 3.7 | 5.9 | 513 | 0.0 |
| Street | – | 254 | 184 | 4.6 | 5.6 | 559 | 0.0 |
| Telephone | – | 101 | 72 | 4.3 | 6.9 | 554 | 0.0 |
| Together | – | 366 | 467 | 5.3 | 2.7 | 567 | 0.0 |
| Water | – | 433 | 1125 | 3.5 | 6.5 | 502 | 0.0 |
| MEAN | | 400.0 | 487.1 | 4.2 | 5.6 | 530.4 | 1.9 |

Geo F, frequency from the geology expert frequency database; Celex F, frequency from the CELEX database (Baayen et al., 1993); WFG, frequency from Educator's Word Frequency Guide (Zeno et al., 1995); AoA, age-of-acquisition rating (in years); Conc, concreteness rating; RT, reaction time from geologists in ms; %Error, error rate for geologists. All frequencies are given in counts per million. *The RTs and error rates for this word are not included in the means (see details in Section 3.2).

**Appendix C**

Word properties and performance data for items in Experiment 3

| Word | Geo F | Celex F | WFG | AoA | Img | RT |
|---|---|---|---|---|---|---|
| *Geology* | | | | | | |
| Basalt | 316 | 0 | 1 | 13.8 | 6.6 | 477 |
| Bearing | 262 | 26 | 13 | 10.8 | 3.9 | 489 |
| Carbonate | 551 | 0 | 2 | 14.4 | 5.7 | 495 |
| Garnet | 356 | 1 | 1 | 13.5 | 6.2 | 471 |
| Glacial | 342 | 1 | 2 | 10.4 | 6.0 | 470 |
| Gradient | 163 | 1 | 1 | 10.2 | 5.4 | 490 |
| Granite | 318 | 6 | 8 | 14.0 | 6.8 | 491 |
| Isotope | 677 | 0 | 0 | 15.8 | 2.7 | 479 |
| Mineral | 552 | 6 | 26 | 10.8 | 5.6 | 442 |
| Plateau | 299 | 6 | 9 | 11.8 | 6.0 | 483 |
| Ridge | 348 | 16 | 17 | 10.2 | 6.1 | 466 |
| Rift | 320 | 2 | 1 | 12.3 | 5.7 | 459 |
| Sample | 816 | 10 | 30 | 10.0 | 3.0 | 459 |
| Sediment | 904 | 2 | 4 | 13.0 | 6.1 | 477 |
| Shear | 605 | 1 | 0 | 12.1 | 5.2 | 458 |
| Strata | 396 | 4 | 2 | 14.6 | 6.3 | 469 |
| MEAN | 451.6 | 5.2 | 7.3 | 12.3 | 5.4 | 473 |
| *Early/Low-frequency* | | | | | | |
| Bite | – | 17 | 21 | 4.0 | 5.1 | 501 |
| Bubble | – | 4 | 6 | 3.7 | 7.0 | 501 |
| Caterpillar | – | 2 | 5 | 4.2 | 6.8 | 502 |
| Glue | – | 3 | 10 | 4.3 | 6.0 | 471 |
| Gorilla | – | 2 | 3 | 4.9 | 6.8 | 502 |
| Greed | – | 8 | 2 | 6.0 | 2.7 | 466 |
| Grumble | – | 2 | 1 | 5.8 | 2.5 | 492 |
| Icing | – | 2 | 1 | 5.5 | 6.2 | 467 |
| Muddle | – | 5 | 0 | 5.8 | 3.1 | 457 |
| Plasticine | – | 1 | 0 | 4.5 | 6.2 | 511 |

(*continued on next page*)

Appendix C (*continued*)

| Word | Geo F | Celex F | WFG | AoA | Img | RT |
|---|---|---|---|---|---|---|
| Rainbow | – | 6 | 9 | 4.2 | 7.0 | 447 |
| Riddle | – | 2 | 3 | 5.8 | 3.2 | 468 |
| Shepherd | – | 6 | 6 | 4.2 | 6.4 | 473 |
| Somersault | – | 1 | 1 | 5.4 | 6.2 | 483 |
| Stripe | – | 2 | 1 | 4.8 | 6.3 | 464 |
| Swan | – | 5 | 3 | 4.8 | 6.6 | 443 |
| MEAN | | 4.3 | 4.5 | 4.9 | 6.5 | 478 |
| *Early/High-frequency* | | | | | | |
| Because | – | 1320 | 1078 | 4.6 | 1.0 | 469 |
| Between | – | 742 | 635 | 5.5 | 2.7 | 464 |
| Country | – | 367 | 390 | 5.2 | 4.5 | 467 |
| Give | – | 484 | 427 | 3.6 | 2.8 | 469 |
| Glass | – | 125 | 129 | 4.4 | 6.8 | 466 |
| Great | – | 667 | 800 | 4.6 | 2.2 | 468 |
| Group | – | 305 | 361 | 5.7 | 3.8 | 474 |
| Important | – | 369 | 610 | 5.6 | 1.8 | 456 |
| Mother | – | 428 | 502 | 3.1 | 6.5 | 440 |
| Please | – | 124 | 73 | 3.3 | 1.7 | 458 |
| Remember | – | 256 | 222 | 5.3 | 1.3 | 471 |
| Right | – | 826 | 777 | 4.2 | 2.3 | 464 |
| Second | – | 340 | 331 | 5.5 | 2.9 | 447 |
| Short | – | 193 | 223 | 4.6 | 4.8 | 455 |
| Sound | – | 167 | 241 | 5.2 | 2.2 | 431 |
| Street | – | 254 | 184 | 4.5 | 6.3 | 424 |
| MEAN | | 435.3 | 436.4 | 4.7 | 3.4 | 458 |

Geo F, frequency from the geology expert frequency database; Celex F, frequency from the CELEX database (Baayen et al., 1993); WFG, frequency from Educator's Word Frequency Guide (Zeno et al., 1995); AoA, age-of-acquisition rating (in years); Img, imageability rating; RT, reaction time from geologists in ms. All frequencies are given in counts per million.

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