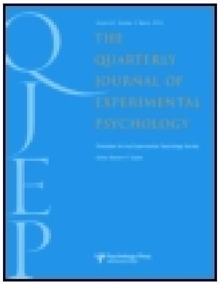

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Short article

What causes the effect of age of acquisition in lexical processing?

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Three hypotheses for effects of age of acquisition (AoA) in lexical processing are compared: the cumulative frequency hypothesis (frequency and AoA both influence the number of encounters with a word, which influences processing speed), the semantic hypothesis (early-acquired words are processed faster because they are more central in the semantic network), and the neural network model (early-acquired words are faster because they are acquired when a network has maximum plasticity). In a regression study of lexical decision (LD) and semantic categorization (SC) in Italian and Dutch, contrary to the cumulative frequency hypothesis, AoA coefficients were larger than frequency coefficients, and, contrary to the semantic hypothesis, the effect of AoA was not larger in SC than in LD. The neural network model was supported.

Effects of word frequency (high-frequency words are processed faster than low-frequency words) and age of acquisition (AoA; early-acquired words are processed faster than late-acquired words) in lexical processing are by now widely accepted as they are found in many different studies and many different tasks (see Ghyselinck, Lewis, & Brysbaert, 2004, for a review). Although these effects are both very stable, the question of where they originate has not been settled. In particular, the effect of word AoA has been less accommodated in models of lexical processing than has the effect of word frequency.

Three proposals on the effect of AoA have been formulated. These are the cumulative frequency hypothesis (Lewis, Gerhand, & Ellis, 2001), the neural network model (Ellis & Lambon Ralph, 2000), and the semantic hypothesis (Brysbaert, van Wijnendaele, & de Deyne, 2000). These proposals are the focus of the present work.

The cumulative frequency hypothesis (Lewis et al., 2001), states that the total number of times that a word has been encountered affects word-processing speed. AoA and frequency effects emerge because both variables influence

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this cumulative frequency of the word. In this view, AoA is replaced by time known (the age of a person minus the AoA of the word). This is because cumulative frequency is influenced by the total time that a word has been known, which changes as a person grows older.

Lewis et al. (2001) demonstrated that the effect of AoA is reconcilable with the cumulative frequency hypothesis, by assuming that learning takes place according to the "Power Law of Practice". This law is widely accepted in the field of learning and states that the time it takes to complete a task diminishes exponentially with the amount of practice. In the cumulative frequency hypothesis lexical processing is a task in which some words have been more practised than others.

Zevin and Seidenberg (2002) tested the effect of cumulative frequency in a connectionist network simulating speeded naming. The orthogonal design had two factors: cumulative frequency and frequency trajectory. Cumulative frequency was the total number of times that a word was presented to the network. Frequency trajectory referred to the presentation pattern of words: Some words were presented often in the beginning and then gradually decreased in frequency, while other words had the reverse pattern. This frequency trajectory resembles AoA, because words encountered often in the beginning of training will be acquired earlier. Zevin and Seidenberg's results confirmed the effect of cumulative frequency and failed to find any independent effect of frequency trajectory.

In a multitask investigation in French, Bonin, Barry, Méot, and Chalard (2004) found effects of cumulative frequency in all tasks, while effects of frequency trajectory were only found in tasks that have arbitrary input–output mappings. Bonin et al.'s (2004) study suggests that while cumulative frequency is an important variable, depending on the task AoA (estimated by frequency trajectory) can have an effect beyond what can be explained by cumulative frequency.

The previous studies notwithstanding, evidence regarding the cumulative frequency hypothesis is mixed. While it has been supported in some studies (Bonin et al., 2004; Lewis et al., 2001; Zevin & Seidenberg, 2002), others have failed to support some crucial predictions. Morrison, Hirsch, Chappell, and Ellis (2002) tested the cumulative frequency hypothesis by comparing AoA effects in object naming and word reading in young and old adults. The cumulative frequency hypothesis predicts that AoA effects should be weaker in older adults because the relative difference in cumulative frequency caused by differences in AoA is smaller for them than for young adults. However, no interaction between age and AoA was found in either task.

Another theory that locates AoA effects in general learning mechanisms is the neural network model advanced by Ellis and Lambon Ralph (2000). This model states that AoA effects occur because as networks are acquiring new materials, they gradually lose plasticity during training and are therefore less capable of changing structure to accommodate new material. This model assumes that AoA effects are due to the order of acquisition of items in a network.

Lewis et al. (2002) compared the cumulative frequency hypothesis with the neural network model in a repetition priming face classification task. The critical difference between the two models is that while the cumulative frequency hypothesis predicts that the regression coefficients of AoA and frequency should be equally large, the neural network model states that AoA has an effect beyond the effect of cumulative frequency. The results favoured the neural network model, as AoA had a larger effect in face classification than did frequency. Ghyselinck et al. (2004) replicated this in an extensive multitask investigation.

The third hypothesis about the locus of the AoA effect is the semantic hypothesis, advanced by Brysbaert et al. (2000), which states that when words are acquired and built into a semantic network, the meaning of later acquired words is necessarily built on earlier acquired words. This gives early-acquired words a more central and better connected place in the network, which could explain why they are more easily processed.

Steyvers and Tenenbaum (2005) describe a model of semantic network acquisition. In this model many kinds of semantic networks are characterized by a relatively small number of highly connected hubs. These very central words have a high number of connections to other words, while other words have a smaller number of connections. This model is congruent with the account outlined above. Evidence for AoA effects in semantic tasks has been found in several studies (for a review see Juhasz, 2005).

The present study is aimed at comparing the three proposals described above. The three models make a number of predictions. The cumulative frequency hypothesis as specified by Lewis et al. (2001) predicts that in a log-transformed regression analysis, regression coefficients for time known (age minus AoA) and frequency should be equally large. This is because time known and frequency are part of the same variable, cumulative frequency. Their weights should therefore be equal. This prediction can be tested in a log-transformed regression, which takes the form of a linear regression of log time known and log frequency on log reaction time (RT). The coefficients of log time known and log frequency should be equal in size since they are derived from the same variable.[1]

If the coefficients for AoA are found to be larger, this favours either the semantic hypothesis or the neural network model, as both these models predict AoA effects beyond what can be explained by cumulative frequency. To distinguish between these two models, a further prediction of the semantic hypothesis can be tested: The effect of AoA should be largest in the task that involves semantics to a larger extent (i.e., semantic categorization). This is because semantic categorization (SC) requires deeper access to word meaning than lexical decision (LD) does. Balota and Chumbley (1984) state that a decision in LD is accomplished in two stages. First, a quick check is made as to whether the word exceeds a familiarity/meaningfulness (FM) criterion. If so, a "yes" response is made. If the word is not sufficiently familiar or does not generate a meaning a more analytical check of the item's presence in memory is made. For SC the response cannot be made on the basis of familiarity and therefore needs to be made on the basis of meaningfulness only. In other words, in SC it is not sufficient to decide whether an item is present in memory, the meaning itself needs to be retrieved in order to make a response. If AoA effects are found to be equal in both tasks, this supports the idea of a general learning mechanism as postulated by the neural network model. In their multitask investigation Ghyselinck et al. (2004) did not find that the effect of AoA was stronger in the semantic task. However, they used a rather peculiar semantic categorization: nouns/first names. We doubt whether this task requires sufficiently deep semantic access compared to LD to conclude that AoA effects are not specifically located in semantics. We therefore retested the semantic hypothesis in a more unequivocally semantic task.

In this study, a living–nonliving SC was compared to LD with pronounceable nonwords. This was done for Italian and Dutch. Both languages have a shallow orthography (Borgwaldt, Hellwig, & De Groot, 2005). Both Zevin and Seidenberg (2002) and Ellis and Lambon Ralph (2000) argue that the transparency of a language's orthography affects the size of AoA effects. This prediction depends on the type of task used and reflects the relation between input and output in a task. When there is a regular input–output mapping, what is learned about early words carries over to later acquired words. This helps in learning later words and therefore weakens any AoA effect due to the order of acquisition. Therefore, the transparency of a language should only affect AoA effects in tasks in which the mapping of spelling to phonology is relevant for responding (e.g., word naming). This was confirmed by Bonin et al. (2004), Burani, Arduino, and Barca (in press), and Zevin and Seidenberg (2002). In tasks as used here, where the mapping between stimulus and response is arbitrary, AoA effects should also be found in transparent languages such as Italian and Dutch.

[1] For a detailed mathematical explanation of this prediction, see Lewis et al. (2001).

To reiterate, we tested the following predictions derived from the three models: For the relative size of AoA and word frequency effects, the cumulative frequency hypothesis predicts that these should be equal while the semantic hypothesis and the neural network model predict that AoA effects are larger than frequency effects. For the relative strength of AoA effects in LD versus SC, the semantic hypothesis predicts that AoA effects are larger in SC while the neural network model and the cumulative frequency hypothesis predict that AoA effects are equal in the two tasks.

Method

Participants

A total of 54 Italian native speakers (27 male and 27 female) and 50 Dutch native speakers (21 male and 29 female) participated in the experiment. The Italian participants ranged between 18 and 34 years of age, with a mean age of 26 years. The Dutch participants' ages ranged between 19 and 26 years, with a mean age of 22 years.

Stimuli

Italian. A total of 132 words (66 living and 66 nonliving) and their values were selected from the database of Italian nouns by Barca, Burani, and Arduino (2002; http://www.istc.cnr.it/material/databaselexvar.htm). Living and nonliving words were matched on AoA, log written frequency, imageability, length, and neighbourhood size (N-size).

AoA is expressed in years, converted from the original mean ratings on a 7-point scale. This conversion was done to allow the calculation of time known, which is age − AoA. Imageability is expressed on a 7-point scale. Frequency values were drawn from the corpus *CoLFIS* (Bertinetto et al., 2005). This corpus includes 3 million occurrences. Frequencies have been recalculated to a corpus size of 1 million tokens. Length is expressed in number of letters.

Dutch. A total of 134 words (67 living, 67 nonliving) were selected from four databases. These were *CELEX* (Baayen, Piepenbrock, & van Rijn, 1993), the AoA-ratings collected by Ghyselinck, de Moor, and Brysbaert (2000) and Ghyselinck, Custers, and Brysbaert (2003), and the imageability ratings collected by van Loon-Vervoorn (1985). Frequency was expressed as word count in a corpus of 1 million occurrences, AoA was expressed in years, and imageability was expressed on a 7-point scale. Length was in letters. N-sizes were calculated by extracting all the neighbours of a word from CELEX. Living and nonliving words were matched on all these variables. The stimulus characteristics are shown in Table 1. Independent samples *t* tests demonstrated that there were no

Table 1. *Characteristics of Italian and Dutch stimuli*

		Living				*Nonliving*			
		Min.	*Max.*	*Mean*	*SD*	*Min.*	*Max.*	*Mean*	*SD*
Italian[a]	AoA	3.00	11.00	6.61	2.18	3.00	11.00	6.45	1.90
	Log frequency	0.07	1.35	0.77	0.33	0.18	1.80	0.67	0.39
	Imageability	3.27	6.48	5.42	0.73	3.07	6.54	5.45	0.82
	Length	4.00	9.00	6.30	1.47	4.00	9.00	6.30	1.51
	Log N-size	0.00	0.95	0.25	0.31	0.00	1.00	0.20	0.28
Dutch[b]	AoA	3.80	10.10	7.11	1.36	4.50	10.50	7.01	1.45
	Log frequency	0.00	1.98	0.79	0.62	0.00	1.85	0.87	0.39
	Imageability	4.43	6.80	6.13	0.53	3.70	6.87	6.05	0.75
	Length	2.00	8.00	5.22	1.51	4.00	9.00	4.99	1.11
	Log N-size	0.00	1.36	0.50	0.43	0.00	1.18	0.60	0.37

AoA = age of acquisition. N-size = neighbourhood size.
[a]$N = 66$. [b]$N = 67$.

significant differences between the living and nonliving sets in each language (all ps $> .1$).

For the lexical decision task an equal number of orthographically legal nonwords were added to the word lists. These nonwords were constructed by changing one or two letters in existing words and were matched to the target items for length. No nonwords were obvious neighbours of target items.

Design

All participants performed both LD and SC. The stimuli were randomly split across the two tasks for each participant. The mapping between hands and responses and the order of tasks were randomized.

Tasks

For LD, participants were asked to indicate for each stimulus whether it was an existing word or not, by pressing one of two keys in the keyboard. For SC, participants had to indicate for each word whether it referred to a living entity or a nonliving entity, again by pressing one of two keys.

Procedure

The experiments were controlled using SuperLab Pro for Windows Version 3.1. and E-prime software, for Italian and Dutch, respectively. Participants were tested individually. They were given written instructions on the computer, in which the need to be both quick and accurate was stressed. Then participants were given a practice session of 20 items for LD and 20 for SC. The experimental session consisted of two blocks (comprising 66 items for Italian, half words and half nonwords, and 67 items for Dutch) for LD, and one block (of 66 or 67 items) for SC. Each trial consisted of a fixation cross for 500 ms, followed by the stimulus, which disappeared when the participant made a response, and a blank screen for 1,000 ms, followed by the next trial. If participants did not respond within 1,400 ms, the stimulus disappeared, and the feedback "out of time" appeared.

Results

All errors, missing responses and RTs more than three standard deviations from the task mean were removed. Table 2 shows the mean RTs per task and category for the remaining responses. Error rates include the total percentage of incorrect and missed/late responses as well as the slow responses that were removed. The items *farabutto* (rascal), *fieno* (hay), *gazza* (magpie), and *miele* (honey) were removed from the Italian data because they caused more than 30% errors in SC. Data from two Italian participants who made more than 20% errors in both tasks was not considered in the analyses. For Dutch, no items or participants were removed.

Regression analysis

To test our hypotheses, we used the repeated measures regression procedure described by Lorch and Myers (1990). This procedure is the equivalent of calculating a regression equation for each participant and averaging the coefficients for the predictors, and it therefore takes into account both item and participant variability. The predictors were AoA, log frequency, imageability, and word length. Table 3 shows the intercorrelations

Table 2. *Mean reaction times and error rates per task and word category*

	Italian						*Dutch*					
	Living		*Nonliving*		*Total*		*Living*		*Nonliving*		*Total*	
	RT	*Errors*	*RT*	*Errors*	*RT*	*Errors*	*RT*	*Errors*	*RT*	*Errors*	*RT*	*Errors*
LD	585	7.1	598	7.2	591	7.1	617	4.5	615	5.0	616	4.8
SC	643	6.7	700	9.7	672	8.2	652	7.2	721	8.0	687	7.6
Total	614	6.9	649	8.4	632	7.7	635	5.9	668	6.6	632	6.2

Note: Error rates in percentages. LD = lexical decision. SC = semantic categorization.

Table 3. *Correlations between independent variables in the regression analyses*

		Log frequency	*AoA*	*Imageability*
Italian	AoA	−0.23*		
	Imageability	0.02	−0.66*	
	Length	0.07	0.14	0.04
Dutch	AoA	−0.05		
	Imageability	−0.15	−0.24*	
	Length	0.06	0.10	0.01

AoA = age of acquisition.
*$p < .01$.

between the predictors. To limit multicollinearity, N-size was not inserted. The correlation between word length and log N-size was − .73 for Dutch and − .64 for Italian. There is much less evidence for an effect of N-size on word recognition than there is for word length. It is true that the correlation between AoA and imageability in the Italian set is also high, but there is strong evidence for effects of imageability in word recognition, and therefore we felt it necessary to insert it in the regression analysis along with AoA. For a review of the effects mentioned, see Burani et al., in press. To avoid collinearity we tried to limit the correlations between AoA and frequency. This succeeded better for the Dutch than for the Italian set, though it is still substantially lower than it is in the database that we took our Italian stimuli from ($r = -.37$). To control for category (living/nonliving) effects, category was inserted as a binary predictor.

Table 4 shows the standardized regression coefficients. For Italian, AoA, log frequency, imageability, word length, and word category all had effects on RTs in both tasks. For Dutch, significant effects were found for AoA, log frequency and word length in LD and AoA, log frequency and word category in SC. For both languages the coefficients for AoA were not larger in SC than LD, contrary to what is predicted by the semantic hypothesis. Since the regression analysis of Lorch and Myers (1990) is performed by subjects and items, it is possible to compare coefficients across analyses using the standard errors. A paired t test between the coefficients of AoA for each language confirmed that the coefficients were not significantly different between tasks (both ts < 1).

Log-transformed regression

To test the cumulative frequency hypothesis, we also performed a log-transformed regression as suggested by Lewis et al. (2001). This means that AoA was replaced by log time known, which is calculated by subtracting AoA from the participant's age. The dependent variable was now log RT. As mentioned in the Introduction, the cumulative frequency hypothesis predicts that in such a regression analysis the coefficients for log time known and log frequency should be of the same size. Note that this prediction concerns the raw coefficients. As can be seen in Table 5, the coefficient for log time known was found to be consistently larger than the coefficient for log frequency in both tasks in

Table 4. *Standardized regression coefficients*

	Italian		*Dutch*	
Predictor	*LD* ($R^2 = .379$)	*SC* ($R^2 = .312$)	*LD* ($R^2 = .354$)	*SC* ($R^2 = .328$)
AoA	.10***	.06**	.06**	.05*
Log frequency	−.14***	−.07***	−.11***	−.05*
Imageability	−.06**	−.10***	.00	−.03
Length	.07***	.07***	.06**	−.01
Category	−.07***	−.23***	−.01	−.22***

Note: Dependent variable = RT. AoA = age of acquisition.
*$p < .05$. **$p < .01$. ***$p < .001$.

Table 5. *Log-transformed regression analysis*

	Italian		*Dutch*	
	LD ($R^2 = .379$)	*SC* ($R^2 = .312$)	*LD* ($R^2 = .354$)	*SC* ($R^2 = .328$)
Predictor				
Log time known (age − AoA)	−.540***	−.329***	−.144***	−.086
Log frequency	−.122***	−.035***	−.019***	−.011**
Imageability	−.028***	−.003***	−.000	−.005
Length	−.016***	−.013***	.003*	−.001
Category	−.041***	−.113***	−.002	−.043***

Note: Dependent variable = log RT. AoA = age of acquisition.
*$p < .05$. **$p < .01$. ***$p < .001$.

both languages (Italian: $T_{LDT} = 2.73$, $p < .01$; $T_{SCT} = 18.82$, $p < .001$; Dutch: $T_{LDT} = 20.83$, $p < .001$; $T_{SCT} = 11.64$, $p < .001$). The correlation between the size of the coefficients for log time known and log frequency for the two tasks and two languages was $r(4) = .87$. Therefore, the effects are very strongly linked but the size of the AoA effect is larger.

Discussion

The results were rather straightforward. Log frequency and AoA had effects on RTs in both tasks in both languages. Contrary to what the semantic hypothesis predicts, the regression coefficients for AoA were not larger in SC than in LD. In the log-transformed analysis performed to test the cumulative frequency hypothesis we found that in both languages the regression coefficients for log time known were larger than the coefficients for log frequency in both LD and SC. This confirms the result found by Ghyselinck et al. (2004) and does not support the cumulative frequency hypothesis.

We compared three models that were developed to account for word frequency and AoA effects in lexical processing. Of these, the neural network model by Ellis and Lambon Ralph (2000) correctly predicted our results. Predictions from the cumulative frequency hypothesis and the semantic hypothesis were both not supported. The cumulative frequency hypothesis predicted that the regression coefficients for AoA and frequency should be equally large, but in both languages we found that coefficients for AoA were larger in both tasks. This replicates the studies of Ghyselinck et al. (2004) and Lewis et al. (2002), favouring the neural network model as the most promising account of AoA.

Crucially, this study provides a convincing comparison between the semantic hypothesis and the neural network model: A more unequivocally semantic task was used than that done by Ghyselinck et al. (2004). The semantic hypothesis predicted that the coefficient for AoA should be larger in the semantic task than in the lexical decision task, but we found it to be smaller, though not significantly so. This result is the first to directly distinguish between the neural network model and the semantic hypothesis. The two models, though very similar, have one important difference: The neural network model claims that AoA effects are a general property of any instance of cumulative interleaved learning—that is, in situations where early acquired items receive continuing practice while more items are being acquired. The semantic hypothesis, on the other hand, makes specific predictions about the type of representations that the AoA effect applies to.

Our findings thus confirm the crucial prediction made by Ellis and Lambon Ralph (2000) that in most tasks AoA and frequency effects should be found together, because both are an inherent property of learning networks. This has been found to be the case in most studies. In their multitask investigation on frequency and AoA effects, Ghyselinck et al. (2004) carried out a linear regression on the regression coefficients for AoA and frequency in eight tasks and found that $r = .91$. The correlation between the sizes of the coefficients for AoA and log frequency in the different tasks and languages in the present study was similar with $r = .87$. These strong correlations imply that AoA and frequency effects can indeed be expected to emerge together, though they do differ in size.

Another prediction of the neural network model was supported in this study. Ellis and Lambon Ralph (2000; see also Zevin & Seidenberg, 2002) expect AoA effects to lie in mappings between different representations. The expectation is that AoA effects will be strongest in cases where what is learned about early-acquired items does not help in learning later items. For instance, learning the pronunciation of early printed words will help the child acquire grapheme–phoneme conversion rules that will also help in learning the pronunciation of later words. On the other hand, learning that TABLE is a piece of furniture will not help the child in learning the meaning of SOFA. The neural network model predicts that AoA effects are strongest in these latter cases. The present study confirms that AoA effects are equally large in different tasks with arbitrary input–output mappings. Ghyselinck et al. (2004) used tasks with arbitrary input–output mappings (lexical decision with legal nonwords or pseudohomophones and semantic categorization) and tasks with regular input–output mappings (naming tasks, perceptual identification, and lexical decision with consonant strings as nonwords). AoA effects were largest in the LD tasks with legal nonwords and pseudohomophones and smaller in the naming tasks, perceptual identification, LD with consonant strings as nonwords, and semantic decision. Therefore, with the exception of semantic categorization, the prediction is confirmed that tasks with arbitrary input–output mappings have larger AoA effects. The fact that, in the study by Ghyselinck et al. (2004), the noun/first-name categorization task patterns with the naming tasks confirms the suspicion that this task does not require sufficiently deep semantic access. We have demonstrated that when a sufficiently deep semantic task is performed, AoA effects emerge that are comparable in size to AoA effects in lexical decision with legal nonwords.

Belke, Brysbaert, Meyer, and Ghyselinck (2005) propose the lexical–semantic competition hypothesis for AoA effects. They claim that there are two AoA effects; one is frequency dependent, and the other is frequency independent. The frequency-dependent effect resides in a common neural learning mechanism for AoA and frequency and therefore is in accordance with both the cumulative frequency view and the neural network model. The frequency-independent effect arises during the mapping of concepts onto lemmas and is therefore found in tasks such as picture naming where a lemma needs to be selected based on a concept. In the two tasks used in our study, lemma selection was not necessary, and therefore only the frequency-dependent AoA effect could be investigated. Our results are therefore also in accordance with this hypothesis, but do not provide strong evidence for it. Further research will be necessary to directly compare the lexical–semantic hypothesis and the neural network model.

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