An Eye Movement Corpus Study of the Age of Acquisition Effect

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Abstract

The current study investigated the effects of word-level age of acquisition on natural reading. Previous studies, using multiple language modalities, found that earlier learned words are recognized, read, spoken and responded to faster than words learned later in life. Until now, in visual word recognition, experimental materials were limited to single word or sentence studies. We analyzed data of the Ghent Eye-tracking COrpus (GECO; Cop, Dirix, Drieghe, & Duyck, in press), an eye-tracking corpus of participants reading an entire novel, resulting in the first eye movement megastudy of AoA effects in natural reading. We found that the age at which specific words are learned indeed influences reading times, above other important (correlated) lexical variables such as word frequency and length. Shorter fixations for earlier learned words were consistently found throughout the reading process in early (single fixation durations, first fixation durations, gaze durations) and late measures (total reading times). Implications for theoretical accounts of AoA effects and eye movements are discussed.

Carroll and White (1973) first discovered that the age at which we learn words influences their processing speed, independent from other language processing determinants. They found shorter latencies for picture naming when words had an earlier age of acquisition (AoA). Since then, AoA effects have been reported in various tasks and language modalities: picture naming (e.g., Belke, Brysbaert, Meyer, & Ghyselinck, 2005), word naming (e.g., Gerhand & Barry, 1999b), masked priming (e.g., Brysbaert, Lange, & Van Wijnendaele, 2000), semantic categorization (e.g., Brysbaert, Van Wijnendaele, & De Deyne, 2000) and lexical decision (e.g., Gerhand & Barry, 1999a). For reviews, see Johnston & Barry (2006) or Juhasz (2005).

Age of Acquisition Hypotheses

Two hypotheses try to explain the mechanism behind the AoA effect. The *semantic hypothesis* claims that AoA effects do not primarily originate from learning lexical word forms, but from their semantic representations. AoA effects then reflect the speed by which these are accessed, as a function of the organization of the representational network (Brysbaert, Van Wijnendaele, et al., 2000; Steyvers & Tenenbaum, 2005). When new concepts are learned, they are linked to the ones already in the network. Early learned words will be more central and better connected in the network, making them more easily accessible. Evidence for this hypothesis comes from the observation that AoA effects become larger when semantic activation of stimuli is necessary; i.e. they are larger in object naming tasks than in lexical decision (Barry, Johnston, & Wood, 2006), and larger in lexical decision than in word naming (Cortese & Khanna, 2007). More direct evidence comes from semantic categorization tasks where AoA effects were found (Brysbaert, Van Wijnendaele, et al., 2000), and from a semantic Simon task (Ghyselinck, Custers, & Brysbaert, 2004). In this last paradigm, participants judged whether words were presented in upper- or lowercase by responding verbally with labels that could be semantically congruent or incongruent with the (irrelevant) meaning of the target ("living" and "nonliving"). The semantic congruency effect was stronger for early acquired words, showing that the meaning of the early learned words was activated faster. The authors conclude that semantics play an important role in the AoA effect.

The second hypothesis is the *mapping* or *connectionist* hypothesis. It originates from simulations with connectionist networks (Ellis & Lambon Ralph, 2000; Monaghan & Ellis, 2010): items that were trained first always had an advantage over later trained items because the early items are learned better. The researchers argue that information which enters a network first, benefits more from the plasticity of the network and alters its connections, or weights, to a stronger extent. As new information keeps on entering the network, the network loses plasticity, making weight changes smaller. Early items thus have a larger impact on the networks final structure. In contrast to the semantic hypothesis, the mapping hypothesis does not situate AoA effects on a single processing level. It could play at the lexical, semantic and/or phonological level. Evidence for this hypothesis comes from tasks where it is shown that learning completely new information (e.g., nonwords, complex patterns, etc.) in several stages results in an order of acquisition (OoA) effect, analogous to the AoA effect (Joseph, Wonnacott, Forbes, & Nation, 2014; Stewart & Ellis, 2008).

Age of Acquisition in Eye-tracking

AoA effects emerge across language modalities, and are therefore also of interest for visual word recognition research, which often use lexical decision tasks (Brysbaert, Lange, et al., 2000). Next to these studies with single word presentations, also eye-tracking has been used to investigate AoA effects in a few rare sentence reading studies (Joseph et al., 2014; Juhasz & Rayner, 2003, 2006). This is highly relevant, given that most words are encountered in a sentence context. It is therefore important to generalize findings from experimental, isolated word recognition, to natural language processing.

One of the advantages of investigating eye movements is that they can be monitored with high spatial and temporal resolution. They reveal large amounts of information on underlying word recognition processes (Rayner, 1998, 2009). Also, multiple dependent variables are available in eye-tracking. Single fixations are the durations of the fixation of words that were fixated only once. First fixations are the durations of the first fixation of words, regardless of later refixations. Gaze durations are the sum of all fixation durations during the first passage before the eyes focus of the word. These measures are “early” measures of eye-tracking because they reflect initial stages of word recognition. Finally, total reading times are a “late” measure of eye-tracking, as they constitute the sum of all fixations on the target word including refixations. As participants only have to read the presented text, another advantage of eye-tracking is the minimal amount of interference by task demands, in contrast to for example the lexical decision, which includes a decision component that may introduce strategic biases. Eye-tracking does therefore seem to be a promising technique to investigate AoA effects in visual word recognition.

Juhasz and Rayner (2003, 2006) found that the AoA of target words influenced reading times in eyetracking: earlier AoAs lead to shorter fixations. In the 2003 study, this was found in early measures (single fixation and gaze duration); in the 2006 study also in an additional early (first fixation) and late measure (total reading time). The authors argue that this difference is due to the design of the studies: in the 2006 study an orthogonal design with early and late AoA values was applied; in the 2003 study, AoA was treated as a continuous variable. The effects were more pronounced when only extreme AoA values were presented. As both studies presented the target stimuli in sentences, and because semantic activation (i.e., the meaning) of these words is necessary to understand the sentence, Juhasz and Rayner interpreted their results as evidence for the semantic hypothesis.

These pioneering eye-tracking studies on AoA effects are very informative and now require assessments of their generalizability. First, the total amount of target sentences (and words) tested by Juhasz and Rayner (2003, 2006) was limited to respectively 72 and 108. This is typical for an eye-tracking paradigm, but rather small compared to the megastudy approach that we adopted here. Second, the researchers operationalize "natural reading", their extension of isolated word recognition, as single sentence reading, whereas in daily life we also tend to read longer chunks of text that make a coherent whole. Finally, although the 2003 study with a continuous AoA yielded significant effects, their most convincing results of AoA effects come from orthogonal designs. Balota, Cortese, Sergent-Marshall, Spieler, and Yap (2004) argued that a factorial approach could entail several flaws, such as implicit biases of experimenters and participants, and a reduction of power and reliability when continuous variables are converted to categorical ones. They propose a megastudy approach as a valuable alternative, with large samples of stimuli varying on a broad range of characteristics. For isolated word recognition, this approach has been successfully applied in two studies (Cortese & Khanna, 2007; Cortese & Schock, 2012) that assessed AoA effects in lexical decision data of the English Lexicon Project (ELP, Balota et al., 2007). Both studies found an AoA effect (faster reaction times for earlier AoA) above and beyond other predictors such as word frequency and length. In compliance with these studies, we assessed AoA effects using megastudy data of natural story reading.

Current Study

We investigated AoA effects in the Ghent Eye-tracking COrpus (GECO; Cop et al., in press). This corpus is an eye-tracking database of participants reading an entire novel. GECO has previously successfully been used to investigate for example effects of word frequency (Cop, Keuleers, Drieghe, & Duyck, 2015) and orthographic neighborhood (Dirix, Cop, Drieghe, & Duyck, in press). Here, we used the corpus to investigate the importance of AoA, in addition to other lexical variables, when participants are reading a large body of text, rather than single words or sentences. The corpus contains a monolingual (English) and a bilingual (Dutch and English) part. For the current study we focused on the monolingual data as we wanted to investigate the AoA effect without potential influences of second language knowledge. The monolingual dataset contains about 760 000 words read in total: 14 participants read 54 364 words (5012 unique), embedded in 5 300 sentences. This dataset provides a large variety in target words and a broad range of word characteristics.

We analyzed both early (single fixation, first fixation and gaze duration) and late (total reading time) measures of eye-tracking. The AoA ratings for our stimuli were taken from the database of Kuperman, Stadthagen-Gonzalez, and Brysbaert (2012). Such ratings are commonly used in AoA experiments and score well on validity (Brysbaert, in press). Next to AoA, we included other (sometimes correlated) important word recognition predictors in the analysis: word frequency (SUBTLEX-UK; van Heuven, Mandera, Keuleers, & Brysbaert, 2013), length and neighborhood density (CLEARPOND; Marian, Bartolotti, Chabal, & Shook, 2012). Several target words were presented more than once throughout the novel, so we included the predictor “rank of occurrence” to account for repetition effects.

We expected that reading times, on all measures, would be shorter for earlier learned words, in accordance with Juhasz and Rayner (2003, 2006). We did not apply an orthogonal design, but we included interactions between the predictors in the base models. This allowed the interaction of AoA with word frequency, as in Gerhand and Barry (1999a). They found that the AoA effect was larger for low frequent words.

Method

Participants and Materials.

The stimuli and data of this study were taken from the monolingual GECO part (Cop et al., in press), in which participants read the entire novel “The mysterious affair at Styles” by Agatha Christie. We included all nouns for which an AoA rating was available in Kuperman et al. (2012), but only if at least 75% of the raters made an AoA estimation (to ensure a reliable AoA rating). 7158 nouns (1487 unique) remained in the final selection (see Table 1).

The monolingual participants were 14 undergraduate students at the university of Southampton (8 females, M_{age} = 21.8, SD_{age} = 5.6). Their language proficiency was tested with the LexTALE (Lemhöfer & Broersma, 2012; M = 91.07, SD = 8.92, range = [71.25 – 100]).

Table 1

Descriptive Statistics for the nouns of the monolingual part of GECO used in the current study, averaged over stimuli (standard deviations between parentheses).

Word Frequency[a]	Word Length	AoA[b]	Neighborhood Density[c]	Rank of Occurrence
3.99 (0.90)	5.85 (2.23)	6.42 (2.47)	4.75 (5.68)	13.40 (19.71)

[a]Log10 Subtlex frequencies from SUBTLEX-UK (van Heuven et al., 2013); [b]Age of Acquisition of the English words (Kuperman et al., 2012); [c]Total neighborhood densities from CLEARPOND (Marian et al., 2012).

Procedure

Eye movements of the participants were monitored while they read the novel in four separate sessions. The number of chapters was fixed for each session, but the reading tempo within the sessions was self-paced. To ensure that participants were reading for comprehension, multiple choice questions were presented after each chapter. For a detailed overview of the procedure, see Cop et al. (in press).

Eye movement analysis

Each dependent variable was fitted in a linear mixed model using the lme4 package (version 1.1-10) in R (version 3.1.1; R Core Team, 2014). P-values were calculated with lmerTest (2.0-30). Initial models included fixed factors AoA, Word Frequency, Word Length, Neighborhood Density, Language Proficiency and Rank of Occurrence (all continuous), and random intercepts for subjects and words. The random intercepts for subjects were included to ensure that individual differences in genetic, developmental or social factors between subjects were modeled (Baayen, Davidson, & Bates, 2008). The random intercept for words were included to be able to generalize to other nouns, as the current stimuli set is not an exhaustive list of all English nouns. Word Frequency was log transformed with base 10 to normalize its distribution. All continuous variables were centered.

Each dependent variable was also log transformed with base 10. The following procedure was applied to discover the optimal model (Barr, Levy, Scheepers, & Tily, 2013): first a full model including all interactions between the fixed effects (up to three-way) was fitted. Then, the model was backward fitted by excluding the interaction with the smallest t-value. An interaction term was excluded if a model comparison Chi-square test turned out to be not significant, meaning that it did not contribute to the fit. Next, the random effects were forward fitted. They were kept in the model if they contributed to the fit. Finally, the fixed effects were again backward fitted.

Results

The average fixation times are presented in Table 2. We median split the data by AoA and word frequency, just to give an indication of the effect sizes of these crucial predictors. The descriptive statistics indicate that their independent effects are comparable in size.

Outliers were determined as fixation times more than 2.5SD away from the subject means and were removed from the dataset (2.16% for single fixation, 2.37% for gaze duration, 2.80% for total reading time). All final models are presented in Table 3. See Supplementary Materials for the first fixation analysis.

Table 2

Average single fixation duration, first fixation duration, gaze duration and total reading time for early [2.4-7.8] and late [7.9-19] AoA and low [0.01-3.44] and high [3.45-5.85] word frequency, in ms.

	Age of Acquisition			Word Frequency		
	Early	Late	Effect	Low	High	Effect
Single fixation duration	216	226	10	226	217	9
First fixation duration	218	232	14	232	219	13
Gaze Duration	234	255	21	256	234	22
Total Reading Time	265	301	36	303	266	37

Single Fixation Duration

Only nouns that received a single fixation were selected for this analysis (56.35%). There was a main effect of AoA: single fixations were shorter for words with an earlier AoA. The main effects of word frequency and word length were significant, as was their interaction. Single fixations were shorter for more frequent words, but only for nouns of 4 or more letters ($\chi = 6.17$, df = 1 $p < .05$). The interaction between word length and language proficiency was also significant. Fixations became longer with increasing word length, but this effect diminished for participants who scored 92.65 or higher on the LexTALE ($\chi = 3.84$, df = 1 $p < .05$).

Table 3

Estimates, standard errors, t-values and p-values for the fixed and random effects of the final general linear mixed effect model for the dependent measures.

	Single Fixation Duration					Gaze Duration					Total Reading Time				
	β	SE	*t*	*p*		β	SE	*t*	*p*		β	SE	*t*	*p*	
Fixed Effects															
Intercept	2.320	0.014	160.806	<.001	***	2.343	0.017	141.872	<.001	***	2.388	0.019	124.878	<.001	***
Age of Acquisition	0.002	0.001	4.272	<.001	***	0.002	0.001	3.632	<.001	***	0.003	0.001	3.178	.002	**
Word Frequency	-0.008	0.002	-4.305	<.001	***	-0.011	0.002	-4.821	<.001	***	-0.013	0.003	-4.478	<.001	***
Word Length	0.002	0.001	2.320	.025	*	0.006	0.001	4.502	<.001	***	0.009	0.001	7.597	<.001	***
Neighborhood Density	<-0.001	<0.001	-0.693	.489		<-0.001	<0.001	-0.048	.962		<0.001	<0.001	0.578	.563	
Language Proficiency	-0.001	0.002	-0.696	.499		<-0.001	0.002	-0.177	.863		<0.001	0.002	0.221	.829	
Rank of Occurrence	<-0.001	<0.001	-0.810	.418		<-0.001	<0.001	-0.644	.520		<-0.001	<0.001	-3.233	.001	**
AoA * Word Frequency	/	/	/	/		/	/	/	/		-0.002	0.001	-3.944	<.001	***
Word Frequency * Word Length	-0.001	<0.001	-2.957	.003	**	-0.001	<0.001	-2.640	.008	**	/	/	/	/	
Word Length * Language Proficiency	<-0.001	<0.001	-2.651	.018	*	/	/	/	/		/	/	/	/	
	Variance	SD				Variance	SD				Variance	SD			
Random Effects															
Word															
(Intercept)	<0.001	0.018				0.001	0.023				0.001	0.033			
Subject															
(Intercept)	0.003	0.054				0.004	0.062				0.005	0.071			
Age of Acquisition	<0.001	0.001				<0.001	0.001				<0.001	0.001			
Word Frequency	<0.001	0.005				<0.001	0.006				<0.001	0.008			
Word Length	<0.001	0.002				<0.001	0.004				<0.001	0.004			

p<0.1 . p<0.05 * p<0.01 ** p<0.001***

Gaze Duration

The main effect of AoA was significant: gaze durations were shorter for earlier learned words. The main effects of word frequency and word length were significant, as was their interaction. Gaze durations were shorter for higher frequent nouns; post hoc contrasts showed that the effect was significant for even the shortest words (3 letters, $\chi = 5.27$, df = 1 $p < .05$) but it became larger as word length increased.

Total Reading Time

The main effects of AoA and word frequency were significant, as was their interaction (see Figure 1): Total reading times were faster for an earlier AoA reading times, but only for words with a word frequency up to 4.290 ($\chi = 3.86$, df = 1 $p < .05$). The main effects of word length and rank of occurrence were significant. Reading times were slower with increasing word length, but faster for repeated presentations of a noun.

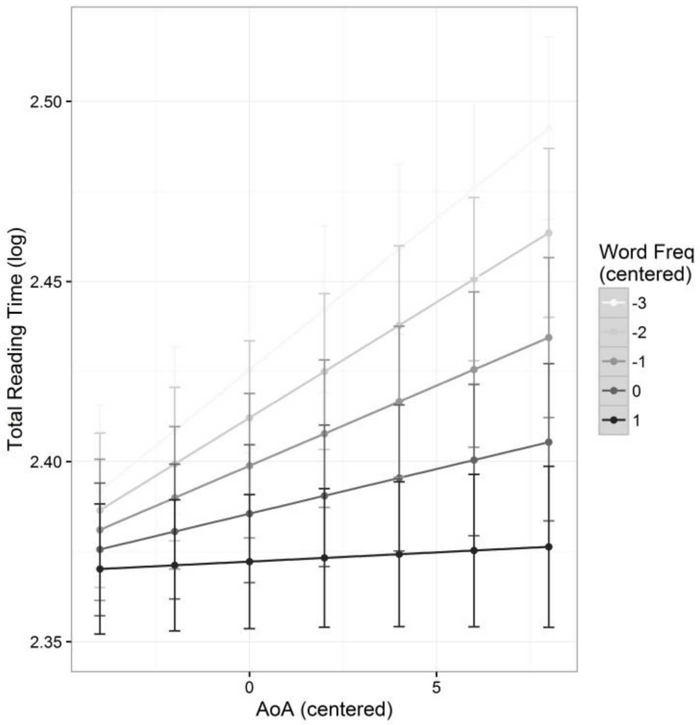

Figure 1. The interaction between AoA (x-axis) and Word Frequency (lines) in Total Reading Times (Y-axis)

Discussion

We investigated AoA effects in the monolingual data of an eye-tracking corpus (GECO; Cop et al., in press). In accordance with a few rare earlier eye-tracking investigations (Juhasz & Rayner, 2003, 2006), we expected faster reading times for earlier learned words. And indeed, we found that AoA had the expected effect on reading times for all four dependent eyetracking measures: earlier learned words were read faster, independent of other lexical variables. Furthermore, we hypothesized that word frequency and AoA could interact. For total reading times, this interaction was indeed significant and in line with previous results (Gerhand and Barry 1999a): the AoA effect was larger for low frequent words.

This study was the first to investigate AoA effects in natural reading. Our results show that the age at which we learn words does not only influence the reading process when encountering single words (e.g., Brysbaert, Lange, et al., 2000) or sentences (Juhasz & Rayner, 2003, 2006), but even when while reading longer pieces of coherent text. The results are also in line with other megastudy investigations of AoA effects on isolated word recognition (e.g., Cortese & Khanna, 2007).

Following the reasoning of Juhasz & Rayner (2003, 2006), semantic activation is needed to understand words embedded in sentences, and AoA effects emerged during such reading. AoA effects were found in measures such as single fixations (where the word is read and recognized on a single fixation) and total reading times, for which we assume that semantic activation of the word is then completed. Indeed, the current results could be considered evidence for the semantic hypothesis (Brysbaert, Van Wijnendaele, et al., 2000), where the semantic network organization plays a central role in AoA effects. However, the current results could also be framed in the mapping hypothesis (Ellis & Lambon Ralph, 2000). This hypothesis does not specify which processing level AoA influences, but handles a “first-come, first-served” principle: network weights are altered in favor of items that entered the network earlier. We also observed AoA effects on measures where semantic access of words is not yet assumed to be complete (i.e., first fixation and gaze duration).

Furthermore, this hypothesis predicts that AoA effects should be the strongest in tasks where input-output mappings are arbitrary, such as in picture naming, where there is no systematic mapping between the meaning of the picture and the phonology of the word it represents. On the other hand, AoA effects should be smaller in tasks where input-output mappings are consistent, like in word naming tasks that usually have a reasonably consistent relationship between the orthography and phonology of a word. Evidence for this prediction was provided both in a computational and an experimental study by Lambon Ralph and Ehsan (2006), where the AoA effect was indeed larger for arbitrary mappings than for systematic mappings. In the current study, we found a significant AoA effect in all timed measures of reading, but the averages in Table 3 indicate that the effect is smaller in early measures (which are supposed to reflect early word recognition) than in late measures (which involve semantic processing of the words and thus rely on the arbitrary orthography – semantic mappings). In addition, the mapping hypothesis predicts AoA effects to be present in opaque languages (with arbitrary orthography to phonology mappings). As English is considered an opaque language, our current results are also in line with this prediction.

A third option is that the AoA effect originates from systems that occur in both the semantic and mapping hypotheses, as they are not mutually exclusive. Indeed, whereas the mapping hypothesis describes a functional mechanism, the semantic hypothesis provides a structural explanation. In the data, early learned words have an overall advantage over later learned words, even in early word recognition stages. This can be explained by the mapping hypothesis. However, the meaning of early learned words is also activated faster, possibly because they have a more central place in the lexicon. As our data points towards evidence for both hypotheses, it is likely that they both have a share in the etiology of the AoA effect.

Next to theoretical accounts of the AoA effect, these results are also of importance to eye movement models. An example is the E-Z reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006). According to this model, lexical processing of words occurs in two serial stages. In the *familiarity check*, lexical candidates become active. After completion of this stage, the oculo-motor system starts programming a saccade towards the next word. In the *verification stage*, full lexical identification of the target word is accomplished. After the completion of this stage, attention is shifted towards the next word. This model thus decouples saccade programming from the attention shift. The determining factors for the duration of the two stages are assumed to be word frequency and predictability of the target. However, the current results suggest that also AoA determines the duration of fixations. For example, the familiarity check might be faster for words that are more easily accessible because they have a more central place in the network (semantic hypothesis) or because the network weights are shifted in their advantage (mapping hypothesis), leading to shorter fixations. Future versions of E-Z reader could introduce AoA as a determining factor for fixation times, hereby possibly increasing the explained variance in observed reading times.

In conclusion, we found clear AoA effects in the eye-tracking patterns of monolinguals reading an entire novel, independent and above the influence of other lexical variables. These results generalize the large body of evidence that finds that earlier learned words are processed faster, to natural reading of running text.

Acknowledgements

This research was funded by a concerted research action, Grant No. BOF13/GOA/032, from Ghent University.

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