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Selective Effects of Age of Acquisition on Morphological Priming: Evidence for a Sensitive Period

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ABSTRACT

Is there an ideal time window for language acquisition after which nativelike representation and processing are unattainable? Although this question has been heavily debated, no consensus has been reached. Here, we present evidence for a sensitive period in language development and show that it is specific to grammar. We conducted a masked priming task with a group of Turkish-German bilinguals and examined age of acquisition (AoA) effects on the processing of complex words. We compared a subtle but meaningful linguistic contrast, that between grammatical inflection and lexical-based derivation. The results showed a highly selective AoA effect on inflectional (but not derivational) priming. In addition, the effect displayed a discontinuity indicative of a sensitive period: Priming from inflected forms was nativelike when acquisition started before the age of 5 but declined with increasing AoA. We conclude that the acquisition of morphological rules expressing morphosyntactic properties is constrained by maturational factors.

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1. Introduction

The question of whether there is an ideal time window for language acquisition has been subject to continuous debate over many years. One prominent proposal, the critical period hypothesis (Lenneberg 1967), states that if language acquisition starts early enough (i.e., before puberty), then successful attainment is guaranteed and similar across individuals. In contrast, later onsets of acquisition—for example, when learning a second language (L2)—rarely yield nativelike outcomes and are characterized by substantial interindividual variability (Bialystok & Hakuta 1999). This proposal has received considerable attention in the cognitive sciences because, if confirmed, it would suggest that language acquisition follows an innately specified maturational schedule (Newport, Bavelier & Neville 2001). However, despite its significance, the hypothesis that there is a critical or "sensitive" period in language development is still controversial.[1]

On the one hand, research with individuals who were deprived of linguistic input (Curtiss 1977; Davis 1947) or with deaf learners of sign languages (Lieberman et al. 2015; Neville et al. 1997; Newport 1990) suggest that the ability to acquire language is susceptible to maturational changes. Specifically, delayed acquisition is associated with profound deficits in grammatical knowledge, but exposure to language before the age of 7 allows for substantially better outcomes.

Research on L2 acquisition, on the other hand, has produced much less of a consensus (see Birdsong 1999). Although many studies have demonstrated a negative correlation between age of acquisition (AoA) and measures of linguistic attainment, even when controlling for L2 exposure and use (for reviews, see DeKeyser 2012; DeKeyser & Larson-Hall 2005; Long 1990), competing accounts—which

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[1]While the term *critical* has historical precedent, the alternate term *sensitive* period was coined to emphasize that "windows of opportunity" for learning may close gradually rather than abruptly (Werker & Hensch 2015).

do not invoke a sensitive period—have also been advanced. For example, age-related declines in ultimate L2 proficiency have been attributed to cognitive aging (Birdsong 2004), socioeconomic factors (Bialystok & Hakuta 1994), or to the progressive "entrenchment" of native language representations (Pallier 2007). In contrast to sensitive period accounts, which postulate that age effects result from the inaccessibility of domain-specific acquisition procedures after a certain maturational point (e.g., Bley-Vroman 1990; Pinker 1984, 1994), the latter proposals appeal instead to general learning principles or to nonlinguistic cognitive factors.

One concern with much previous research that makes it hard to assess the relative merits of these accounts is that the question of whether there is a privileged period for acquiring *language* may in fact be misguided. This is because language consists of distinct knowledge systems (phonology, syntax, etc.) and processing mechanisms (lexical access, syntactic computation, etc.), each governed by their own specific principles (Jackendoff 2002). Hence, effects of AoA can be expected to be selective, or to be more pronounced in some linguistic domains than others (Granena & Long 2013; Huang 2014). That is, whereas some subsystems of language acquisition may exhibit sensitive periods that start "closing" in early childhood, other subsystems may remain fully operational until later in life or even throughout the life span (Eubank & Gregg 1999; Long 1990; Pulvermüller & Schumann 1994; Werker & Hensch 2015).

A related observation concerns the linguistic measures that have been employed in previous research. Most studies have used global proficiency scores, like self-ratings of linguistic ability (e.g., Bialystok & Hakuta 1999; Hakuta, Bialystok & Wiley 2003), or measures of "linguistic output," such as grammaticality judgments (e.g., Johnson & Newport 1989; Flege 1999). However, due to their generality, such measures may not be sensitive enough to detect selective AoA effects. For example, if a specific type of linguistic knowledge is compromised as a result of its late acquisition, but the language user is able to compensate for that loss through other intact systems (Bley-Vroman 1990), then nativelike performance in general proficiency tasks may in fact arise from non native like representations and processing (Felser & Cunnings 2012). In sum, an appropriate assessment of age effects and of whether they arise from a maturationally guided sensitive period may require subtle measures of processing that tap into specific linguistic domains (Abrahamsson & Hyltenstam 2009).

Experimental studies that have investigated different linguistic domains suggest that AoA effects may indeed be selective. For example, while semantic anomalies elicited similar brain responses in early and late bilinguals, syntactic violations yielded more widely distributed activation patterns for late bilinguals (Weber-Fox & Neville 1996; Wartenburger et al. 2003). Similarly, although basic syntax can be nativelike even when acquired later in life (Newport 1990), the processing of complex syntactic dependencies is "shallower" in late learners, who instead rely more on lexical and semantic information (Clahsen & Felser 2006). These results suggest that delayed acquisition does not affect "language" as a whole, but selectively modulates *grammatical* processing, a view which is consistent with a domain-specific sensitive period (Newport, Bavelier & Neville 2001).

In the present study, we investigated the role of AoA in the processing of linguistic morphology, comparing two superficially similar subtypes, derivation and inflection, that nevertheless differ in whether they involve lexical or grammatical operations—a subtle, but meaningful linguistic contrast. Derivational operations create new lexical entries (e.g., *govern* → *government*), which carry additional (possibly idiosyncratic) semantic information, and behave linguistically like any other entry in the lexicon. In contrast, inflection (e.g., *walk* → *walks*) is purely grammatical, in that it adds little semantic content, but spells out (morpho)syntactic features like person, number, or tense. In many linguistic frameworks, derivation and inflection involve two distinct kinds of morphological knowledge (Anderson 1992; Stump 2001): word-formation rules, which map one lexical entry onto another (for derivation), and rules of morphosyntactic realization, which map between features and forms (for inflection). If the sensitive period in language acquisition is, in fact, restricted to specific aspects of *grammatical* knowledge, then we may find selective AoA effects on the processing of inflected, but not derived, forms.

A different aspect of the debate that bears on whether age effects can be ascribed to maturational changes concerns the shape of the function that relates AoA to linguistic measures. If language acquisition is indeed constrained by a sensitive period, then there should be a "discontinuity" at the offset of this period (Singleton 2005), that is, the relation between AoA and linguistic measures should be qualitatively different within and outside a specified age band (Johnson & Newport 1989).

One can think of two broad types of discontinuous geometries that would constitute persuasive evidence for a sensitive period (Birdsong 2014; Hakuta, Bialystok & Wiley 2003; see also Birdsong 2006). First, the AoA function may show a "stretched-L" shape—that is, a (negative) AoA effect on linguistic measures for those participants whose immersion in the target language started early in life, followed by weaker or absent AoA effects when exposure to an L2 occurs later (see a graphical depiction on Figure 1, top middle graph). This is the geometry that has been most commonly obtained in previous empirical studies, and it is interpreted as resulting from maturational changes during early childhood, which are followed by a leveling off of age effects once the sensitive period has completely "closed" (e.g., DeKeyser, Alfi-Shabtay & Ravid 2010; Flege, Yeni-Komshian & Liu 1999; Johnson & Newport 1989). Second, the AoA function might show a "stretched-7" shape—that is, nativelike attainment for a range of early AoAs (i.e., a flattened slope, with small or null AoA effects), coupled with stronger AoA effects at later ages (see Figure 1, top left graph). Such a geometry indicates a "window of opportunity" for acquiring language early in life, followed by a progressive decline in learning ability (Birdsong & Molis 2001; DeKeyser 2000). In the current study, we made use of nonlinear analytical techniques (viz., regression-with-breakpoints) to compare the fit of these theoretical geometries to the relation between AoA and the online processing of complex words.

2. The present study

As mentioned, the present study contrasted the processing of derived and inflected forms in word recognition. There are indications that pronounced differences between early and late learners can be found in the domain of inflection (e.g., Johnson & Newport 1989; McDonald 2000). In a sentence completion task in Dutch, for example, Blom, Polišenská & Weerman (2006) found that, relatively to child (L1 and L2) learners, adult L2 learners not only omitted inflectional suffixes more frequently but also overgeneralized specific suffixes to inappropriate syntactic contexts. Blom, Polišenská & Weerman proposed that while children can make use of syntactic cues to build nativelike inflectional paradigms

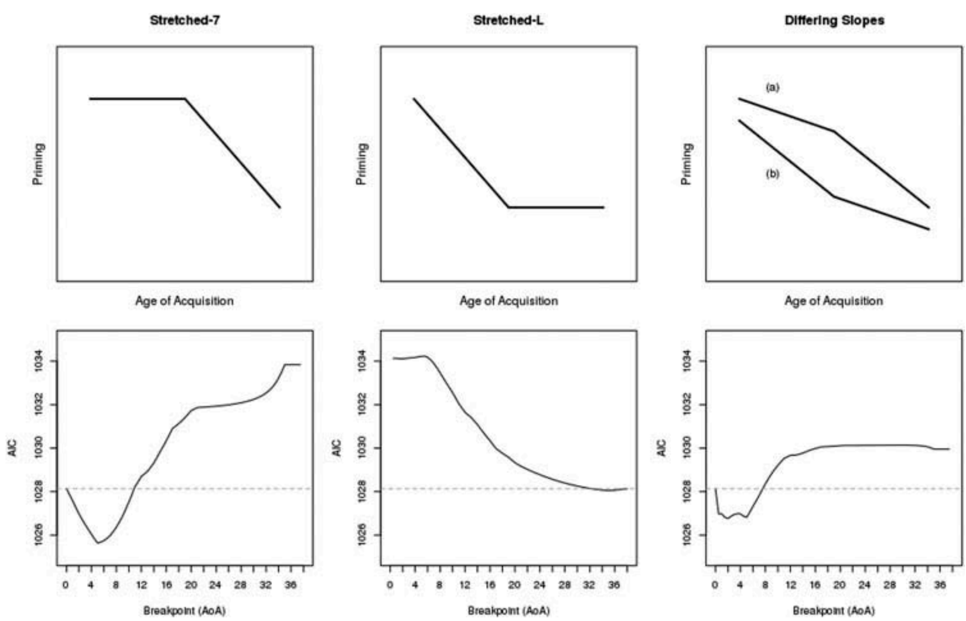

Figure 1. AIC scores (i.e., goodness of fit) for regression-with-breakpoints models, with successive breakpoints at different values of the AoA scale (bottom panels), for each of the three geometric configurations shown on the top panel (see Birdsong 2014).

(i.e., structured sets of rules that map syntactic features to affixes), late learners create paradigms that are "relatively small" and "underspecified" (p. 333; see also Pinker 1984 for a paradigm-based model of the acquisition of inflection). More generally, the vulnerability of L2 inflection has been attributed to impairments in certain syntactic features of the L2 grammar (Meisel 1997) or in the overt morphological realization of these features (Prévost & White 2000). Critically, however, such grammatical impairments should not affect the representation of *derivational* rules, which do not express morphosyntactic information but create new lexical items.

Here, we investigate the long-term consequences of acquiring an L2 at different ages to the automatic, unconscious processes involved in the recognition of complex words. Importantly, the influence of AoA was estimated while statistically controlling for L2 proficiency, exposure, and use, so that any AoA effects cannot be attributed to correlations with other linguistic variables. We hypothesized that when acquisition occurs relatively late in life, then inflectional (but not derivational) rules are particularly difficult to acquire and will not be efficiently deployed in the recognition of inflected forms. As an index of the application of morphological rules in processing, we made use of the masked priming technique, which is considered to be particularly sensitive to morphological structure. Specifically, masked priming is notorious for revealing robust effects of morphological relatedness, but small or absent effects of semantic overlap, as well as null or inhibitory effects between orthographically related words (e.g., Davis & Lupker 2006; Rastle et al. 2000; Rastle, Davis & New 2004; Segui & Grainger 1990). Because of these properties, masked priming effects between morphologically related words are thought to indicate access to the component parts of a complex word (Marslen-Wilson 2007; Rastle & Davis 2003). Nevertheless, we also ensured that any facilitation effects between morphologically related words were indeed morphological in nature by examining priming between semantically and orthographically related words.

We tested a large sample of L1 Turkish speakers who acquired German at a range of different ages and compared priming effects from German derived and inflected forms on the recognition of the same target word. If the acquisition of derivational rules remains nativelike throughout the lifespan, then AoA should not modulate derivational priming. In contrast, if the acquisition of inflectional rules is compromised for late-learners, then inflectional priming effects should be reduced with increasing AoA. In addition, the relation between AoA and inflectional priming may show a discontinuous shape, indicating an early period of nativelike processing ("stretched-7" configuration) or a leveling off of AoA effects ("stretched-L" configuration).

3. Method

3.1. *Participants*

Ninety-four bilingual participants were recruited from the Turkish-German community in Berlin. This group provides a range of different language profiles, which allowed investigating the effects of AoA within a single community, while controlling for the influence of other variables. To precisely estimate priming effects in native (bilingual) speakers of Turkish, as well as assess whether these effects were modulated by AoA of German, we attempted to represent in our sample three commonly considered "bilingual types" (in approximately equal numbers): (i) simultaneous bilinguals (AoA of German of 0–3 years), most of whom acquired Turkish and German from birth; (ii) early bilinguals, who learned German as an L2 in early childhood (but after the age of 3); and (iii) late bilinguals, who acquired German after the age of 10. These selection criteria ensured that the distribution of AoA values had sufficient range and variation to allow both linear and nonlinear regression analyses.

One participant was excluded because s/he was found not to have acquired Turkish as his/her first language. Therefore, we processed and analyzed the data from 93 participants (55 male). Table 1 provides the summary statistics for the language profiles of these participants, as obtained from background questionnaires. All participants had normal or corrected-to-normal vision, did not report any language-related disorders, and were paid for their participation.

Table 1. Means and Ranges of Demographic Measures.

Variable	Mean	Standard Deviation	Range
Age of Acquisition (years)	6.69	7.49	0–38
Proficiency (Goethe score, out of 30)	24.89	4.20	11–30
Length of Exposure (years)	20.32	7.31	4–40
Use of German (average percentage)	43.97%	18.54%	1.55%–85.83%

3.2. *Demographic measures*

The following predictors of interest were calculated and tested for their effect on morphological priming. *AoA* is the self-reported age (in years) at which participants actively started learning German. *Length of Exposure* is a (rough) measure of exposure to German, quantified as the number of years since the reported onset of acquisition. *Proficiency* is a measure of competence in German, as assessed by the Goethe Institute Placement Test, a 30-item multiple-choice test assessing lexicon and grammar. *Use of German* is a measure of everyday use and exposure to German, calculated as an average of self-reported percentages of use on a typical week (Birdsong, Gertken & Amengual 2012; Marian, Blumenfeld & Kaushanskaya 2007).[2]

These four predictors were simultaneously included in all regression analyses. This allowed us to control for any correlations between AoA and our measures of language proficiency, exposure, and use. Specifically, estimates in multiple regression reflect the unique variance of each predictor (i.e., the part of each variable that cannot be predicted by all others in the regression model); therefore, effects are interpreted as the "pure" contribution of each variable, beyond any correlations with the others (e.g., Wurm & Fisicaro 2014).[3]

3.3. *Materials*

The experiment employed three different item sets—morphological, orthographic, and semantic (taken from Jacob, Heyer & Veríssimo 2017). The morphological set consisted of 28 infinitival targets (e.g., *prüfen* 'to check') preceded by either a derived nominalization (e.g., *Prüfung* '(the) check'), an inflected participle form (e.g., *geprüft* 'checked'), the target form itself (i.e., *prüfen*), or an unrelated prime (e.g., *Spiegel* 'mirror'). Derivational and inflectional affixes both consisted of three letters added to the verbal stem, allowing properties that may play a role in orthographic priming to be perfectly matched: length of primes, number of letters of the target stem that are present in the prime, and relative order of these letters (see, e.g., Peressotti & Grainger 1999). Unrelated primes (half nouns and half adjectives) were semantically and orthographically unrelated to the target. Unrelated and identity primes were matched with respect to length in letters. In addition, because word frequency is known to have strong effects on word recognition times, all four prime types were matched for word form frequency (see Table 2 for summary statistics). Frequency measures for primes and targets were also inspected to ensure that the experiment did not contain rare words that late-learners were unlikely to know.

The two control item sets, semantic and orthographic, consisted of 24 targets each. Target properties (word form frequency, lemma frequency, length in letters) were comparable for morphological, orthographic, and semantic sets. Each semantic and orthographic target was preceded by three types of primes: unrelated, related, and identity.

[2]Two participants lacked full demographic information, although they completed the masked priming experiment and reported their AoA of German (the key predictor in our study). Specifically, one participant did not report his age (used in calculating Length of Exposure); another did not report his Use of German and did not complete the Proficiency test. We employed regression imputation to predict the three missing covariate values on the basis of all other demographic information from these participants (Gelman & Hill 2006).

[3]However, because Length of Exposure is calculated using AoA (i.e., it is equal to chronological age minus AoA), we ensured that our results were robust to this degree of collinearity by repeating all analyses without Length of Exposure as a covariate. These analyses produced exactly the same statistical effects.

Table 2. Stimulus Properties for the Materials in the Current Study.

Condition	Word-Form Freq. (per Million)	Lemma Freq. (per Million)	Length (Number of Letters)
Morphological set			
Unrelated primes	23.1	62.8	6.3
Derived primes	27.6	37.2	7.8
Inflected primes	22.1	82.6	7.9
Targets	23.8	82.6	6.4
Orthographic set			
Unrelated primes	32	91.2	6.5
Related primes	31.6	83	6.8
Targets	36.3	71.5	5.5
Semantic set			
Unrelated primes	83	150	5.1
Related primes	107.6	142.8	5.1
Targets	86.3	120.1	4.8

Orthographically related primes shared a similar number of letters with their targets as the morphological items. Half of the items mimicked the word-initial overlap in derivational primes (e.g., *Kasten* 'box'—*Kasse* 'cash register'), and the other half the word-middle overlap of inflectional primes (e.g., *Engel* 'angel'—*Geld* 'money'). The semantic set consisted of noun-noun pairs, half synonyms (e.g., *Doktor* 'doctor'—*Arzt* 'physician') and half associates (e.g., *Wolke* 'cloud'—*Himmel* 'sky'). Semantic relatedness was determined in a 7-point rating experiment with 20 German native speakers (mean relatedness: 5.2). Unrelated primes were matched to semantic and orthographic test primes in word category, length in letters, and word form frequency.

Experimental items were distributed across four lists in a Latin Square design, with each participant seeing each target only once. The 76 experimental targets were mixed with 324 fillers, so that half of all targets were pseudowords (overall relatedness ratio: 19%). Item presentation was pseudorandomized within each list and the order reversed for approximately half of the participants.

3.4. *Procedure*

Each participant was randomly assigned to one list. Participants were instructed to decide as quickly and accurately as possible whether each stimulus was a word or not by pressing "Yes" and "No" buttons on a gamepad. A trial started with a 500 ms blank screen, a 500 ms forward mask (hash marks), a prime word displayed for 50 ms, a target word for 500 ms, and a blank screen until a response was made (trial timeout = 5,000 ms). Participants then responded to the background questionnaire and completed the proficiency test.

3.5. *Data processing*

We calculated accuracy rates and mean (correct) RTs for each participant and experimental item. Data cleaning started by removing subjects or items with low accuracy rates (<70%) or that displayed extremely slow responses. This procedure led to the exclusion of two items (*Schlips* 'tie,' from the semantic set, accuracy = 49.5%; *Scheck* 'check,' orthographic set, 61.3%). Two participants were removed due to extremely long mean RTs (over 1,100 ms), which were more than 3 SDs above the average of mean RTs (643 ms, *SD* = 142 ms).

Incorrect responses and timeouts were removed (5.08% of the remaining data). To normalize the dependent variable and reduce the influence of outliers, RTs shorter than 250 ms (3 data points) or longer than 2,000 ms (24 data points) were discarded (0.42% of correct responses), and analyses were conducted on the logarithm of RTs.

4. Results

4.1. *Linear mixed-effects models*

We employed mixed-effects linear regressions, with crossed random effects for participants and items, separately for the morphological, semantic and orthographic sets. The following fixed effects were included: (i) Prime Type as a four-level factor (Unrelated, Inflected, Derived, Identity) or, in the case of the semantic and orthographic control conditions, a three-level factor (Unrelated, Test, Identity); (ii) the continuous predictors AoA, Proficiency, Length of Exposure and Use of German; (iii) interactions between Prime Type and each of these continuous predictors; and (iv) Trial Position (i.e., the rank of the item in the list). Prime Type was coded with treatment contrasts, with the Unrelated level defined as the baseline. Therefore, estimates for the levels of Prime Type reflect *priming effects*—that is, differences between RTs following related and unrelated primes. All continuous predictors were centered around their means, except for AoA, which was included in its original scale. In this way, estimates for Prime Type show priming effects at an AoA of 0, and estimates for continuous predictors reflect the effect for Unrelated primes. To reduce the probability of Type I errors without sacrificing statistical power, we followed the recommendation of Matuschek et al. (2015) and included random slopes if they improved model fit (as measured by AIC). All possible random structures of Prime Type, AoA, and their interaction were assessed. The best models for the morphological and orthographic sets contained no random slopes; the best model for the semantic set contained a by-subject Prime Type slope.

For the items primed by *morphologically related* forms, mean RTs in each condition (back-transformed from mean of log RTs) were 640 ms (Unrelated), 628 ms (Inflectional), 609 ms (Derivational), and 585 ms (Identity). Table 3 displays the estimates and statistics from the mixed-effects regression model.

The estimates at an AoA of German of 0 show shorter RTs after inflected, derived, and identical forms than after unrelated primes. That is, bilinguals who acquired both Turkish and German from birth show repetition priming, as well as robust priming for both types of morphological relation. Despite their similarity at the earliest AoA, the three types of priming were differently affected by this variable. Facilitation produced by inflected participles significantly interacted with AoA, decreasing as AoA increased. In contrast, priming effects elicited by derived and identical forms remained approximately constant throughout the AoA scale. The other predictors of interest—Proficiency, Length of Exposure, and Use of German—showed no effect on RTs and did not interact with any of the priming effects.

Table 3. Results from a Mixed-Effects Model on Log RTs for Items in the Morphological Set.

Predictor	Estimate	Std. Error	t Statistic	p Value	
Intercept (Unrelated primes, AoA = 0)	6.4500	0.0335	192.73	<.001	*
Prime Type INF (inflectional priming, AoA = 0)	−0.0416	0.0176	−2.36	.018	*
Prime Type DER (derivational priming, AoA = 0)	−0.0591	0.0175	−3.37	<.001	*
Prime Type ID (repetition priming, AoA = 0)	−0.0998	0.0176	−5.68	<.001	*
AoA (age of acquisition, Unrelated primes)	0.0014	0.0036	0.37	.710	
Proficiency (Goethe score, Unrelated primes)	−0.0003	0.0066	−0.05	.962	
LoE (length of exposure in years, Unrelated primes)	−0.0017	0.0032	−0.53	.596	
Use (percentage of German use, Unrelated primes)	0.0006	0.0014	0.45	.654	
Trial Position	−0.0001	0.0000	−1.88	.060	
Prime Type INF × AoA	0.0044	0.0020	2.17	.030	*
Prime Type DER × AoA	0.0017	0.0020	0.82	.414	
Prime Type ID × AoA	0.0019	0.0020	0.95	.342	
Prime Type INF × Proficiency	0.0042	0.0037	1.12	.264	
Prime Type DER × Proficiency	0.0048	0.0037	1.28	.200	
Prime Type ID × Proficiency	0.0040	0.0037	1.10	.272	
Prime Type INF × LoE	0.0005	0.0018	0.29	.774	
Prime Type DER × LoE	0.0022	0.0018	1.24	.216	
Prime Type ID × LoE	0.0007	0.0018	0.37	.714	
Prime Type INF × Use	0.0001	0.0008	0.10	.916	
Prime Type DER × Use	−0.0009	0.0008	−1.13	.260	
Prime Type ID × Use	−0.0008	0.0008	−1.02	.310	

*$p < .05$.

The results of mixed-effects regressions on the *semantic* and *orthographic* item sets revealed only repetition priming (t = –4.92 and t = –5.19 respectively) but no semantic or orthographic priming (t = –1.28, t = 1.14) and no interactions (all $|t|$s < 1.25).

In sum, AoA selectively modulated inflectional priming, with facilitation effects gradually declining as AoA increased. AoA did not interact with any other priming effect (i.e., derivational, repetition, orthographic, and semantic).

4.2. *Regression-with-breakpoints*

We examined whether the selective effect of AoA on inflectional priming showed discontinuities by analyzing by-participant priming effects with *regression-with-breakpoints*. The dependent measures were inflectional and derivational priming for each participant, which were calculated by averaging log RTs in each Prime Type condition, back-transforming (i.e., exponentiating) the obtained means and calculating the difference (in milliseconds) between the relevant conditions.

Regression-with-breakpoints allows combining two linear regressions into a single model, with different slopes at each side of a breakpoint (Baayen 2008; Neter et al. 1996). The models were fitted by first creating a numeric variable that takes the values 0 or 1 for participants with an AoA smaller/equal or greater than the breakpoint. To obtain estimates of the AoA effect at each side of the breakpoint, the model contained the interaction between the indicator variable and the AoA variable (centered around the breakpoint), as well as the three covariates that were employed previously (viz., Proficiency, Length of Exposure, and Use of German).

We tested three different classes of theoretical models (shown in Figure 1, top panel), which have been proposed as possible geometries for a sensitive period (see Birdsong 2014): (i) "stretched-7," in which inflectional priming is constant from an AoA of 0 until the discontinuity point and then decreases afterwards; (ii) "stretched-L," in which the decrease in priming is present at early ages but plateaus after it reaches the breakpoint; and (iii) "differing slopes," in which the slope of the AoA priming function is less pronounced (but not flat) on one side of the breakpoint than the other.[4] For each of the three configurations, we followed a breakpoint discovery procedure (Baayen 2008; Vanhove 2013). Specifically, at each interval of 0.5 years in the AoA scale, we stipulated a breakpoint, estimated the regression parameters, and recorded the model's goodness of fit. The goodness of fit of each model was quantified by its AIC. This measure allows comparing nonnested models (which is required because a simple linear regression is not technically nested within the "stretched-7" and "stretched-L" configurations) and takes into account both model fit and complexity (which is advantageous because the "differing slopes" configuration is more complex, in that it requires an extra parameter to be estimated).

The AIC of each type of model at each possible breakpoint is displayed in Figure 1, bottom panel (the higher the goodness of fit, the smaller the AIC value). The AIC of a linear model is shown by a dashed gray line. Models that fit the data better than a linear regression have an AIC value below the dashed line. The optimal model was a "stretched-7" regression with a breakpoint at age 5. This model was significantly better than a linear regression, as indicated by the difference in AIC (2.50), as well as by comparisons of nonnested models (Clarke test, p = .006; Cox test, p = .039).

The breakpoint model is plotted in Figure 2 (full line). It shows significant inflectional priming until an AoA of 5 (b = 23.45, t = 2.88, p = .005), after which priming decreases at a rate of 4.05 ms per year (t = –2.92, p = .004). Inflectional priming was not predicted by Proficiency (b = –2.38, t = –1.09, p = .278), Length of Exposure (b = 0.10, t = 0.10, p = .920), or Use of German (b = –0.21, t = –0.46, p = .647).[5] For comparison, Figure 2 also displays a

[4]A "stretched-L" model is fitted by reversing the values of the (numerical) indicator variable. A "differing slopes" model is fitted by converting the indicator variable to a factor (see Baayen 2008).

[5]To ensure that the specific nonlinear shape that we obtained was not driven by a small number of data points with very high AoAs, we repeated the breakpoint discovery procedure after excluding the two participants with the highest AoAs (35 and 38; see Figure 2). In this analysis, the best breakpoint model showed precisely the same pattern of significant and nonsignificant results (albeit with a slightly later breakpoint, at an AoA of 6).

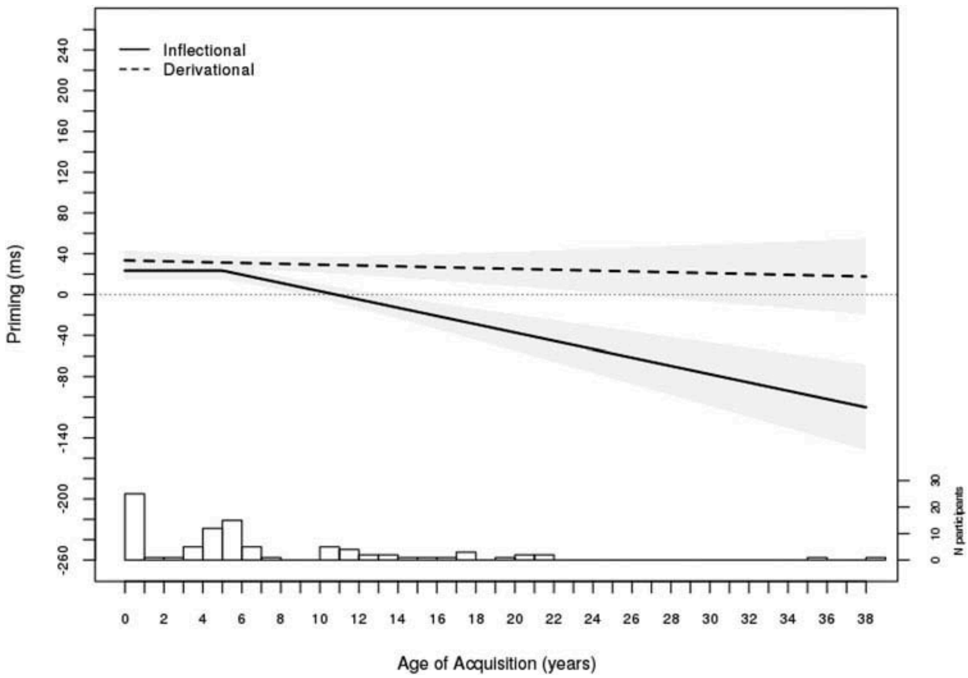

Figure 2. Regression-with-breakpoints model for the effect of AoA on inflectional priming (full line). A linear regression for derivational priming is also shown (dashed line). Gray areas represent pointwise ±*SE* of predicted means. A histogram (bottom, right axis) shows the number of participants at each point in the AoA scale (an analysis without the two participants with the largest AoA produced very similar results; see Footnote 5).

linear regression on by-participant derivational priming (dashed line). As in the mixed-effects analysis reported above, this regression showed significant derivational priming at an AoA of 0 (b = 33.42, t = 3.33, p = .001), but no modulation by AoA (b= –0.41, t = –0.36, p = .721), or by any other predictors (all ps > .367).

The "stretched-7" geometry of AoA effects on inflectional priming was also tested through separate linear regressions on two subsets of participants: those who acquired German before or after the breakpoint at age 5. We estimated the effect of AoA on inflectional and derivational priming (while controlling for other covariate predictors) and in addition, on the *difference* between those effects. For those participants who acquired German before age 5 (n = 44), AoA did not predict inflectional priming (b = 6.70, t = 1.24, p = .224), derivational priming (b = 6.15, t = 0.99, p = .327), or their difference (b = –0.55, t = –0.11, p = .912). In contrast, for those who acquired German at or after the age of 5 (n = 47), increasing AoA was associated with a greater difference between inflectional and derivational priming (b = 3.96, t = 2.67, p = .011), and with a smaller inflectional priming effect (b = –3.87, t = –2.09, p = .043)—but not with the magnitude of derivational priming (b = 0.09, t = 0.06, p = .955).

5. Discussion

We have examined effects of age of onset of L2 acquisition on the automatic, unconscious processes by which (visually presented) morphologically complex words are recognized. Our main finding is an effect of AoA on masked morphological priming. Crucially, this effect was found to be selective, in that AoA only modulated the processing of inflected forms but not of derivationally related forms. Facilitation from derived forms was obtained irrespective of AoA, indicating that even when language is acquired later in life, the ability to access the base stem of derived words is preserved (e.g., hunter → [[hunt]er]). In contrast, the relationship between AoA and inflectional priming revealed a discontinuity indicative of a sensitive period: facilitation effects that indicate stem access (e.g., hunted → [[hunt]ed]) were obtained when L2 acquisition started before the age of 5, but inflectional priming decreased sharply with increasing AoA.

What changes at age 5 such that, when tested many years later, participants who acquired their L2 after that age can process derived but not inflected forms in terms of their component parts? We believe that this contrast can be explained by differences between early- and late-learner's knowledge of morphology and ultimately by differences in the way that inflectional systems are acquired in childhood versus later in life.

According to Pinker (1984), the acquisition of inflection first requires the construction of word-specific *paradigms*, a collection of a word's inflected forms for the grammatical contexts they occur in (e.g., <*walks*, 3sg>, <*walked*, past>, etc.). Subsequently, and progressively, the learner constructs structured sets from which common material like stems and affixes can be extracted (*walk, -s*, *-ed*, etc.). The outcome of this learning process is *generalized paradigms*, a set of rules or rulelike operations for mapping grammatical functions to affixes (e.g., X → X*ed*, +past). In line with proposals that late-learners construct generalized paradigms that are smaller and not appropriately constrained (Blom, Polišenská & Weerman 2006), we suggest that the ability to extract inflectional rules via paradigm-based learning is progressively compromised after early childhood, due to impairments in the representation (Meisel 1997) or use of (morpho)syntactic features (Prévost & White 2000). If that is the case, the acquisition of derivational rules, which do not express morphosyntactic information and are not paradigmatically organized, may be immune to a sensitive period. Indeed, our finding that derivational priming is not modulated by AoA indicates that such morphological operations can be acquired in a nativelike way throughout the life span. More generally, we suggest that there is no sensitive period for acquiring "language" but for the acquisition of specific kinds of *grammatical* knowledge.

The selectivity and nonlinearity of the obtained AoA effect also call into question nonmaturational accounts of the relation between age and language acquisition. It is hard to see how, for example, socioeconomic factors (Bialystok & Hakuta 1994), cognitive aging (Birdsong 2004), or L1 influence (Pallier 2007) could explain the differential effect of AoA on inflection, but not derivation, and why this effect should be restricted to a particular age band. Furthermore, the effect of AoA on inflectional priming was obtained while controlling for measures of L2 proficiency, exposure, and use, which suggests that the influence of age at the onset of acquisition is independent of linguistic attainment and of amount of linguistic input. Instead, our results suggest that the constraints that govern the acquisition of grammar are within the learning organism (rather than in exogenous factors) and are subject to a maturational schedule (Long 1990; Newport, Bavelier & Neville 2001).

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