Masked identity priming reflects an encoding advantage in developing readers

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The masked priming technique is widely used to explore the early moments of letter and word identification. While this technique is increasingly used in experiments with young readers, the mechanism in play during masked priming with early readers has not yet been fully explored. We investigate the masked priming effects from a modeling perspective; we instantiate competing theories as data models (using Bayes Factors) and as a computational model (diffusion model). We carried out a masked priming experiment using identity primes with second and fourth-grade participants, and we analyzed the data through an evidence accumulation model lens. The priming effect manifests as a shift in the RT distribution, which in evidence accumulation models is accounted for by changes in the encoding process. We describe such changes as savings that have three features of theoretical importance: (1) They are numerically very close to the SOA between primes and targets; (2) They remain relatively constant from second to fourth grade; (3) They seem to operate at the level of abstract orthographic representation because the priming effect occurs in both case-matched and case-mismatched pairs. These findings also have consequences for the practice of data transformation in developmental research: some patterns of data, when transformed, would produce spurious effects.

Key words: masked priming; young readers; modeling; lexical decision
Since its inception, Forster and Davis’ (1984) masked priming technique quickly became the most popular paradigm aimed at unveiling the early moments of letter and word identification (see Grainger, 2008, for a review). In this technique, a forward mask is replaced on the screen by a briefly presented prime stimulus (≈30-50 ms), which in turn is replaced by the target stimulus until the participant makes a response (typically a lexical decision). This paradigm allows researchers to manipulate the prime-target relationship (e.g., identity, orthography, phonology, semantics) in the absence of conscious identification of the prime.

The masked priming technique was initially employed with adult readers (Forster & Davis, 1984), but it has also become a gold standard for comparing orthographic processing in young readers of different grades (e.g., Acha & Perea, 2008; Castles, Davis, Cavalot, & Forster, 2007; Kezilas, McKague, Kohnen, Badcock, & Castles, 2017; Lété, & Fayol, M, 2013; Soares, Perea, & Comesaña, 2014; Ziegler, Bertrand, Lété, & Grainger, 2014). While using masked priming with developing readers, an interpretability concern is that the longer response times for younger than for older children makes it challenging to compare the magnitude of masked priming effects across age groups. To address this concern, previous masked priming experiments that compare across groups have typically used transformed data (e.g., z-scores: Ziegler et al., 2014; log-transformed or inverse-transformed data: Acha & Perea, 2008). However, any response time transformation makes assumptions about the nature of the task and how masked priming is modulated by age (we revisit the consequences of transformations in the Discussion).
In the current study, we modeled masked identity priming in lexical decision with developing readers. We chose masked identity priming over other forms of prime-target relationships because it produces the most robust effects, and also because there are theoretical accounts in the form of quantitative models that explain the nature of the effect. In this study, the prime and the target were either the same (prime: arte, target: ARTE) or unrelated (prime: kiwi; target: ARTE). The mainstream interpretation of masked identity priming is that the prime activates the letter representations at an abstract level, and this provides an encoding advantage for the identity primes over unrelated primes (i.e., “savings” account; see Forster, 1998). That is, an identity prime presented for 50 ms would give a head start to the processing of the target word of around 50 ms compared to an unrelated prime. The savings account makes a straightforward prediction: The response time (RT) distributions of the identity and the unrelated condition in masked priming should differ merely in a shift in their location (i.e., there should be a similar effect of priming across all quantiles). One could argue that the difference in the RT of unrelated vs. related items could be due to a benefit provided by the identity prime or due to the cost induced by the unrelated prime. This issue was addressed by Jacobs, Grainger, and Ferrand (1995), who demonstrated, using a within-subject baseline, that masked identity priming is essentially due to the facilitation from the related prime and not to the inhibition of an unrelated prime.

In a paper focused on modeling masked priming with adult readers, Gomez, Perea, and Ratcliff (2013) found that masked identity priming produced a shift in the RT distributions (see left panel of Figure 2 in Gomez et al., 2013). To account for their data, they set up two competing implementations of the drift-diffusion model for the
lexical decision task (Ratcliff, Gomez, & McKoon, 2004). In one of the implementations, the priming effect was assumed to affect the encoding processes (the $T_{er}$ parameter of the model); in the other, it was assumed to affect the rate of evidence accumulation (the drift-rate parameter of the model). The distributions’ shift was best accounted for by the model that assumed that masked priming affects the encoding processes, which supports Forster’s (1998) saving hypothesis.

In the Gomez et al. (2013) study, the size of the shift in the RT distributions was virtually identical to the SOA; thus, the main question we address in the current paper is whether masked identity priming in developing readers can also be modeled as a savings process in an evidence accumulation model (i.e., a shift in the RT distributions similar in size to the stimulus-onset asynchrony [SOA]) or whether it produces a different pattern: either quantitative (i.e., a shift in the RT distributions larger or smaller than the SOA) or qualitatively (i.e., a change in shape in the RT distributions). While we use Ratcliff’s drift-diffusion model as our tool, similar distinctions between encoding and decision processes exist in other models (see Brown & Heathcote, 2008); in Figure 1 and its caption we explain how the distinction between encoding and decision processes in the model can generate different predictions in the distribution of RTs.

[Insert_Figure_1_here]

The second goal of the experiment was to examine the effect of matching the case (lowercase-UPPERCASE vs. UPPERCASE-UPPERCASE) of primes and targets. Jackson and Coltheart (2001) postulated that developing readers can access abstract orthographic representations once they can name letters in both uppercase and
lowercase forms. This suggests that, even in second grade, masked identity priming occurs to the same degree for pairs like house-House and House-House (Jacobs et al., 1995, for evidence with adult readers). Perea, Jiménez, and Gómez (2015) replicated the findings of Jacobs et al. (1995) with adults and Grade 5 children; however, their findings with Grade 3 children were inconclusive. Here, we re-explore this issue with Grade 2 and Grade 4 children using a higher number of observations per condition and a model-based approach (see Soares et al., 2014, for a similar choice of grades).

To summarize, in the present work we explore if there are invariances in masked priming (e.g., if case-matching does not affect the priming effect, or if the effect of priming is the same at the two grade-levels). Given this agenda, we have chosen Bayes factors as our tool for statistical inference. Bayes Factors are a way to quantify the evidence in favor of one model over another model in principled ways.

Method

Participants

The participants were 40 second-graders (mean age: 7 years 4 months, with range: 6.8 to 7.8) and 22 fourth-graders (mean age: 9 years 3 months, with range: 8.1 to 9.9) from a public school in Spain. Parental consent was collected for all the participants before the experiment. The sample size was larger for second graders because their latency data are substantially noisier than in fourth grades. All participants were native speakers of Spanish with normal scores on standardized reading/cognitive tests, and with normal/corrected-to-normal vision.

Materials
We selected forty Spanish words of four letters from the Spanish EsPal subtitle database (Duchon, Perea, Sebastián-Gallés, Marti, & Carreiras, 2013) with a mean frequency of 59.9 per million (range: 0.5-325.1). All these words appeared in the LEXIN database (Corral, Ferrero, & Goikoetxea, 2009) for first-grade textbooks. The average number of orthographic neighbors was 6.55 (range: 0-23). We also created forty orthographically legal pseudowords of four letters to act as foils (e.g., TISE; NAIS; VUCA). The list of word and pseudoword targets is presented in the Appendix. Targets were presented in uppercase and they were preceded by either: i) a matched-case identity prime (e.g., ARTE-ARTE); ii) a lowercase identity prime (e.g., arte-ARTE); iii) an unrelated word/pseudoword in uppercase; or iv) an unrelated word/pseudoword in lowercase. Each target stimulus was presented in each condition four times (i.e., 160 word trials, 160 nonword trials), resulting in 40 identity trials and 40 unrelated trials per condition.¹

**Procedure**

The experiment took place in groups of three/four participants in a quiet room. DMDX software (Forster & Forster, 2003) was employed to present the stimuli and register the responses. Stimuli were presented in the center of the screen using the Courier New font. The structure of each trial was as follows: i) a pattern mask (#####) was presented for 500 ms; ii) a prime item was presented for 33.3 ms; iii) a post-mask (#####) was presented for 16.6 ms; and iv) a target item was presented until the participant responded or 3 seconds had passed. Thus, the prime-target SOA was 50 ms—the post-mask was presented to avoid perceptual continuity of primes and

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¹ Previous research has revealed that the nature of masked identity priming in lexical decision is similar when the items are presented once or when they are repeated several times (see Perea, Jiménez, & Gomez, 2014).
targets in the matched-case identity condition. Participants were instructed to press the “yes” key if the uppercase letter string was a Spanish word and refrain from responding if the letter string was not a word, and both speed and accuracy were stressed in the instructions. The 320 stimuli were divided into two lists in a Latin square design so that every participant took part in two sessions in two different days (160 trials each day). In each session, fourteen practice trials preceded the experimental phase. There was a short break around the middle of each experiment session. Each session lasted about 12 minutes.

Results

Error responses (7.6% of all responses for second graders and 4% of all responses for fourth graders) and RTs shorter than 300 ms (less than 0.2% of all responses for both grades) were excluded from the RT analyses—note that RTs could not be longer than the 3,000 ms trial deadline.

We present the results from this study in four different sections. First, we examine if there is an effect of case-matching between primes and targets. Second, we analyze the average latency data and the accuracy data. The third section explores the distributional features of the latency effects using delta-plots. The final section presents a diffusion model account of the developmental trajectory of masked identity priming.

Effect of case-matching

The RTs and accuracies for case matched vs. mismatched identity prime-target pairs are all numerically similar. The mean RTs for related pairs are, for second graders: match = 1090 ms vs. mismatch = 1097 ms, and for fourth graders: match = 911 ms vs
mismatch = 906 ms. The accuracies are similar as well, for second graders: match = .910 vs. mismatch = .919, and for fourth graders: match = .976 ms vs mismatch = .972 ms. Here we examine if there is, in fact, evidence supporting of a lack of case-match effect (Modelₐ: there is a null effect for case match, Model₁: there is a non-zero effect of case match, for both models, we assume an effect of fixed effect of grade and prime-target relation, and random effects of participants and items). Indeed, for the RT, there is a $BF_{0,1} = 33$ and for accuracy there is a $BF_{0,1} = 17$—for these inferential analyses, we used the R package BayesFactor (Morey & Rouder, 2018) with default priors. Given these results, we decided to simply collapse the two conditions (case-match and case-mismatch) in the subsequent analyses.

**Latency Data**

Having established that case match between prime and target seems to play no role in the obtained priming effects, we now examine if the data are consistent with one of the following models:

*ModelₐGrade*: A model in which there is an effect of *grade* only not of *prime*.

*ModelₐFull*: A model in which there are main effects and interaction of *prime* and *grade*.

*ModelₐMain*: A model in which there are only main effects of *prime* and *grade*.

*ModelₐPrime=50ms*: In this model, we assume a main effect of *grade*, and also that the effect of identity priming in our groups (2nd vs. 4th grade) is the same as the prime-TARGET SOA.

In all models, *prime* (identity vs. unrelated), *grade* (Grade 2 vs. Grade 4) were fixed effects while *subjects* and *items* were random effects.
The main-effects only model ($Model_{Main}$) is preferred over the full model: $BF_{M,F} = 160$, meaning that given the data, the main-effects only model is 160 times more likely than the full model (main effects plus interaction). The main-effect model is also preferred over the grade-only model and $BF_{M,G} = 1.06$.

When we compare $Model_{Main}$ to $Model_{Prime=50ms}$, the latter is preferred. Simply put, this model assumes that the priming effect is a 50 ms savings in every identity primed trial: $BF_{50,M} = 42$.

**Accuracy Data**

The results from the accuracy analyses are straightforward. As can be seen in Table 1, participants were quite accurate (on average even second grade students had accuracies over .9 both for words and nonwords).

For word trials, the preferred model was the $Model_{G}$, as older children have higher accuracies, whereas there seems to be no effect of prime type on accuracy. The $BF_{G,M} = 613$. Furthermore, if we compare $Model_{G}$ to an entirely null model as the denominator (i.e., a model in which there are no other effects other than the random effects of item and subject), the Bayes factor is $BF_{G,0} = 37$. For nonword trials, the preferred model was the null model with Bayes factors $BF_{0,G} = 8.8$, and $BF_{0,M} = 5415$.

**Distributional analyses**

In mental chronometry studies, an examination of RT distributions is often done by computing the RTs at specific quantiles, and then, if there are critical conditions to be compared, by analyzing the quantile-quantile residuals. One of these methods is called delta-plots (see Ridderinkhof, 2002). Delta-plots display the RT difference between two
experimental conditions as a function of processing time. The four hypotheses described in the Introduction make differential predictions on the delta-plots.

Illustrations with simulated data are shown in the top panels of Figure 2:

- **Priming provides an encoding head-start.** The effect of masked would be a shift in the RT distribution numerically identical to the prime-target SOA; hence, according to this hypothesis the delta-plot should be flat with an intercept of 50 ms.

- **A head start, but with a different size than the SOA.** The delta-plot is flat, but with an intercept different from the prime-target SOA.

- **Priming effect may reveal differences in the decision process.** In developing children, the effects of priming cascade beyond the encoding process into the decisional component and, hence, there is not only a shift in the delta-plot but also the differences between the identity and the unrelated conditions are larger for the slower responses than for the faster responses; therefore, the delta-plot begins at near 50 ms but has a positive slope and grows for higher quantiles.

The bottom Panels (2nd grade and 4th grade) of Figure 2 shows the empirical delta-plot comparing the RT distributions for related and unrelated primes. The priming effects are best described as a flat line around 50 ms for both age groups. It is worth discussing the dip in the final quantile in the empirical delta-plots for both age groups, we believe that the dip in the .9 quantile is due to slow responses being contaminated by distraction—this would reduce the priming effect.

[Insert Figure 2 about here]

**Diffusion model fit**
The presented results show a fairly clear picture of the effects of priming as a shift in the RT distribution. Furthermore, this shift is about the same size in second and fourth-grade students. We fit the diffusion model (see Ratcliff et al., 2004) to the averaged data. The goal of this fit is to implement the savings in encoding hypothesis in the context of a well-established model, and to confirm that this implementation provides a good account of the empirical data.

For each participant and each condition, the RTs at the .1, .3, .5, .7, and .9 quantiles we calculated for “word” responses (recall that this was a go/no-go lexical decision experiment). Then, these RTs at quantiles were averaged across participants of the same grade level. The response probabilities were also averaged across all participants for each grade. The fitting routine aims to minimize the difference between predicted and the empirical proportion of responses within a time bin (see Ratcliff & Tuerlinckx, 2002).

Given the empirical findings, we decided to allow all parameters to vary between the two age groups, and the $T_{er}$ parameter (the encoding time parameter) to vary as a function of prime-target relationship. Notably, the $T_{er}$ parameter for second graders went from .831 sec for unrelated primes to .769 sec for identity primes (a .062 effect) whereas for fourth graders it went from .534 to .486 (a .048 sec effect)—note that both values are very close to the 0.054 sec effect in $T_{er}$ reported by Gomez et al. (2013).

Discussion

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2 Other parameters of the model: For 2nd graders: $a = .138$, $z = 0.05$, $s_z = 0.025$, drift for words = 0.136, drift for nonwords = -0.143, eta = 0.010, $s_\eta = 0.241$, $p_0 = .003$. For 4th graders: $a = .151$, $z = 0.05$, $s_z = 0.093$, drift for words = 0.253, drift for nonwords = -0.258, eta = 0.092, $s_\eta = 0.008$, $p_0 = .0003$. 
The main goal of this research was to examine whether masked identity priming in developing readers (Grade 2 and Grade 4) can be modelled as a savings effect (i.e., an identity prime would enjoy an encoding advantage over an unrelated prime; Forster, 1998)—note that this is the case in adult readers (Gomez et al., 2013). While the masked priming technique has become a common tool to examine the early moments of word reading in children, there is a gap in the literature as to whether the nature of the processes underlying masked priming differ from those in adult readers. We conducted a masked identity priming experiment with second and fourth grade children in which we manipulated the prime-target relationship in two ways: case match vs. mismatch (for identity pairs), and unrelated primes vs. identity primes.

The effect of case-matching (e.g., arte-ARTE vs. ARTE-ARTE) was null. Targets were always presented in upper case; yet, the case of primes did not affect the RT or the accuracy; there is an invariance between case-matched and case-mismatched trials even in the youngest group of readers. This supports the idea that as early as second grade, readers can encode to the orthographic representation for letters in the first moments of word processing, as tracked by masked identity priming (see Jackson & Coltheart, 2001).

Furthermore, the empirical and modeling results support the hypothesis of masked identity priming tapping into the same underlying mechanisms in second and fourth grade children. Masked identity priming produces a shift in the RT distribution regardless of the grade of the participants; this shift is remarkably similar for the two groups (50 ms). As predicted by Forster’s (1998) savings hypothesis, the magnitude of this shift is similar to the prime-target SOA. This was so despite the fact that the overall
RTs are much larger and noisier for second graders. Given the straightforward nature of the data, it is not surprising that the Bayes factors, delta plots, and diffusion model fits all provide converging evidence in favor of the same hypothesis. Our approach here has been to explore the most tractable form of masked priming: identity priming with no further lexical, semantic or morphological manipulations. Future research should explore this issue along with other types of prime-target relationships and word frequency (see Forster & Davis, 1984: Grainger, Lopez, Eddy, Dufau, & Holcomb, 2012).

To conclude, we would like to emphasize the theoretical and the practical implications of our findings: from the theoretical point of view, we reaffirm the idea that masked identity priming can be thought as a head start in the encoding process (Forster, 1998). Such encoding process is orthographic, not sensory, as masked identity priming is not modulated by the match-mismatch between the letter-case of primes and targets in second and fourth readers (see also Forster, 1998; Perea, Vergara-Martínez, & Gomez, 2015, for parallel evidence with adult readers). Within a drift-diffusion model, this is captured by the $T_{cr}$ parameter. This parameter is assumed to be related to encoding processes that translate the perceptual information into the evidence that is accumulated in the decision process (see Brown & Heathcote, 2008 for a similar parameter within other forms of evidence accumulation models).

A corollary of our study is a warning about transformations of RT data in developmental studies. For this, we will refer back to Figure 1. There are two main patterns of results that occur in latency-based tasks in cognitive psychology: (1) Distributional shifts; and (2) Changes in the shape of the distribution. In this paper,
masked identity priming effect produced a shift while age of readers changes the shape of the distribution with smaller variance in the RTs of fourth grade students. If we transform the data scaling by variance (or SD), we would find an interaction between age and priming. Our process model guides our decision not to transform the data; and we encourage researchers to consider their processing assumptions as they decide to transform or not to transform their data (see for example Faust, Balota, Spieler, & Ferraro, 1999, for an discussion of when transforming is advisable).
References


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https://doi.org/10.1037/a0035187
Table 1. Descriptive statistics for all conditions. The Presented SE are calculated across participants.

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Figure Captions

**Figure 1.** Graphic representations of the four hypotheses being examined. In all panels we represent the encoding process as a flat line; during this time, the retinotopic sensory signal is encoded into orthographic representation but the decision about lexical status has not started. The beams of color represent different average paths of evidence accumulation in one trial (in this case it is evidence in favor of a “word” decision). Note that these are beams to represent the variability across trials in this evidence accumulation. When evidence reaches a decision boundary (the top horizontal line), a response is initiated. Each panel shows the RT distributions for the hypothesis being illustrated. In Panel A, we represent a null hypothesis in which there is no priming effect. In Panel B, we represent the hypothesis that priming in developing readers is identical to the SOA between prime and target (about 50ms savings in the encoding process, the 50ms is represented by the dashed vertical lines). In Panel C, we represent the hypothesis that priming is of different size than the duration of the SOA (in the case of the illustration the effect is larger; note, however, that this hypothesis is agnostic about the direction of the difference). Lastly, in Panel D, we represent the hypothesis that priming in developmental readers affects both the encoding and the evidence accumulation processes.

**Figure 2.** The top panels represent the prediction of the four hypotheses under consideration. Within each panel the graph on the left side shows the RT distribution, and the graph on the right side is the corresponding delta plot. The bottom panels
show the empirical Vincentized RT distributions and the delta delta-plot for second and fourth graders respectively.
Appendix. List of words and pseudowords in the experiment

Words: DEDO; DEJA; CAER; CERA; RATA; ALTA; BATA; BAÚL; TELE; LEÑA; UNIR; CIEN; VINO; SEIS; VIVA; CINE; CASI; MIMO; SUMA; VIVO; ALGA; ANDA; PEGA; AMAR; ARTE; EDAD; GIRÁ; REJA; ARMA; OLER; CITA; BICI; KIWI; MISA; CUNA; IMÁN; CIMA; NUCA; MINA; IRIS

Pseudowords: EDGA; REVA; DAKE; WEDE; MEER; DERU; EMAB; EGTE; BAME; AMEG; VUME; NUVO; ITÉN; BITU; TISE; CISE; MISE; NAIS; CEVI; CONU; ETDA; CEHE; BEÑE; GIAL; ERED; EBTA; BIRE; GAJE; ELMA; OBAR; VUCA; MUWI; CUVE; ETUC; IVIR; CUEK; NIME; NOCE; NITE; ORIM
A. Null Effect

The beams of evidence accumulation paths start at the same point in time and are identical. RT distr. are on top of each other.

B. Effect in encoding time=SOA

The beams of evidence accumulation paths are parallel, the RT distributions are shifted by same amount as the prime–target SOA.

C. Effect in encoding time > SOA

The beams of evidence accumulation paths are parallel, the RT distributions are shifted by more than the prime–target SOA.

D. Effect in encoding & evidence accumulation

The beams of evidence accumulation paths start at diff times and have different average slopes, the RT distr. have different shapes.