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Watching the Brain during Meaning Acquisition

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Acquiring the meaning of a new word in a foreign language can be achieved either by rote memorizing or, similar to meaning acquisition during infancy, by extracting it from context. Little is known about the brain mechanisms involved in word learning. Here we demonstrate, using event-related brain potentials, the rapid development of a brain signature related to lexical and semantic processing during contextual word learning. Healthy volunteers engaged in a simple word-learning task were required to discover the meaning of a novel word from a context during silent reading. After 3 exposures, brain potentials to novel words in meaningful contexts were indistinguishable from real words, although this acquisition effect was not observed for novel words, for which sentence contexts allowed no meaning derivation. Furthermore, when the learned novel words were presented in isolation, an activation of their corresponding meaning was observed, although this process was slower than for real words.

Keywords: event-related potentials, language learning, meaning acquisition

Introduction

"To make children understand what the names of simple ideas or substances stand for, people ordinarily show them the thing whereof they would have them have the idea and then repeat to them the name that stands for it." This is how the British Empiricist Locke envisioned the word-learning process in 1690 (Locke 1964). Indeed, the link between word form and meaning is at the core of human language, and the explosive growth in the vocabulary of children has attracted the interest of scholars from St Augustine in the fourth century (Augustinus 398) to Quine (1960) and Pinker (1984). The acquisition of word meaning involves, at its most basic level, the process of mapping concepts onto specific sounds or signs. This mapping is arbitrary, that is, the same pattern of sounds could correspond to different meanings in different languages. We are constantly encountering new words during all the stages of development, and it has been estimated that between the age of 2 and 20 years, the number of words learned per day ranges between 6 and 25 words (Nagy and Anderson 1984; Landauer 1986). The estimates of the size of vocabulary of high-school graduates and college students range from 40 000 to 100 000 words (Nagy et al. 1987; Sternberg 1987). Most of these words are learned in high school, simply from contextual reading and without explicit instruction. This remarkable word-learning ability is crucial if we consider that new or novel words are constantly created in each language (e.g., slang words, technical words, etc.) and that most people are faced with the challenge of learning at least one new language during their life. The aim of this project is to understand how the meaning of a new word is created in a specific linguistic context.

In the very first stages of word learning, infants have to glean the link between a word and its corresponding object from extralinguistic information with current evidence suggesting that they use sophisticated pragmatic strategies to infer the referential intentions of the speaker in the mapping process in addition to mere statistical association between a word and an object or action (Tomasello and Akhtar 1995; Baldwin et al. 1996; Bloom 2002). Simple word-to-world pairings do not suffice to learn "hard words" such as verbs, however, because these often do not correspond to concrete basic-level concepts (Gillette et al. 1999; Gleitman et al. 2005). When word learning begins, the only source of information available to the child is the observation of the intentional acts of the speakers in conjunction with the heard word (word-to-world mapping). The majority of a child's first words are thus concrete nouns. These provide the basis upon which language will be built. As the child accumulates linguistic experience, less concrete words such as verbs, adjectives, adverbs, and conjunctions are learned. A number of experiments have demonstrated that children in this stage are sensitive to the linguistic context in which a new word appears and that they use the information provided by this context to determine its meaning (Hall and Graham 1999; Subrahmanyam et al. 1999; Cain et al. 2003; Hall and Belanger 2005; Fernald and Hurtado 2006). Moreover, an extensive corpus analysis of child-directed speech (CDS) showed that only a 7% of CDS utterances were comprised of single words. Rather, short simple frames (such as "Look at the...") combined with different content words made up 50% of CDS (Cameron-Faulkner et al. 2003). Therefore, once a certain vocabulary and syntax has accrued, linguistic information can and must be used as an additional source in the word-learning process, thus adding a structure-to-world mapping strategy to the earlier available processes. This more advanced word-learning strategy is similar to the one employed by adult learners of a second language (Singleton 1999; Groot 2000) and will be explored in the present investigation.

Word learning has been studied using the human simulation paradigm (Gillette et al. 1999): adults are exposed to a novel word and the available linguistic or extralinguistic information that can be used to infer its meaning is systematically varied. Unsurprisingly, in one recent study (Gillette et al. 1999), correct identification of novel verbs jumped from 8% in an observation condition entailing silenced video of mother–child interaction to 90% in a condition, which provided the entire utterance (minus the target word) plus the video of the conversation situation.

The aim of the present investigation is to get a first glimpse at the neural correlates of word learning in a variant of the human simulation paradigm that provided linguistic context information. Specifically, young adult native speakers of Spanish were required to silently read triplets of sentences in order to derive the meaning of a novel word that appeared in the terminal position of each of these sentences (see Table 1). Novel words respected the phonotactic rules of Spanish and were thus pronounceable (see Appendix 1 for the complete list). In all cases, the hidden "target" word (like "car" for "lankey" in Table 1) was a concrete Spanish noun of medium frequency (mean 58.1 per one million words) (Sebastian-Gallés et al. 2000). For each target word, 3 sentences were constructed (in total 585), in which an increasing degree of contextual constraint was created. Contextual constraint was measured in an independent paper-and-pencil test in different participants that had to fill in the missing last word of each sentence (see Materials and Methods). Increasing contextual constraint across the triplet ensured that participants could gradually narrow down the meaning of the new word. A second behavioral pretest in 15 young volunteers (195 new words in sentence triplets) yielded a correct identification of the meaning in 91.12% of the cases.

The main event-related brain potential (ERP) (Munte et al. 2001) experiment featured 2 further conditions in addition to the condition in which participants could derive the meaning of the novel word (henceforth meaning condition, M+). In the no meaning (M–) condition, participants could not assign meaning to the novel word because unrelated sentences were used. In the third real-word (R) condition, existing Spanish words were presented in the terminal position of the sentences for comparison.

To rule out the possibility that the observed ERP pattern is due to participants "giving up" in the M– condition, a self-paced reading experiment was conducted in a different group of volunteers, providing a measure of the time needed to process each word of the sentence (Mitchell 1984).

Finally, to test whether the association between the novel word and its meaning generalizes to other contexts, an additional study employing the same word-learning ERP design in a new group of participants was used. This time, however, an additional test was conducted in-between the different learning blocks (i.e., every 24 trials). Novel words from the M+ condition were presented either before their real-word counterpart (e.g., in Table 1 "lankey"—"car"; stimulus duration, 200 ms; onset asynchrony between words, 500 ms; see Materials and Methods for further details) or preceding a different unrelated real word ("lankey"—"house"). A control condition contrasting semantically related (e.g., money—coin) and unrelated (e.g., money—horse) pairs of real words was also used. Participants had to indicate by a button press, whether or not the 2 words were semantically related. The N400 component of the ERP was used as an index of the amount of facilitation of the processing of the second word (Kutas and Hillyard 1989; Holcomb 1993; Swaab et al. 2002). We hypothesized that learning of the novel words should lead to a reduced amplitude of the N400 for immediately following real-word counterparts.

Table 1

Word-learning task
M+ condition
Mario always forgets where he leaves the lankey
It was expensive the repair of the lankey
I punctured again the wheel of the lankey
M− condition
I have bought the tickets for the garty
On the construction site you must wear a garty
Everyday I buy 2 loaves of fresh garty
R condition
She likes people with nice and clean teeth
In a fight Mary had broken 2 teeth
After a meal you should brush your teeth

Note: Participants were required to discover the meaning of a novel word at the end of each of 3 successively presented sentences (each 8 words in length). In the M+ condition, the meaning of the novel word was readily apparent, whereas in the M− condition, no meaning could be mapped to the novel word, as the 3 sentences each required a different terminal word. To control for the repetition effects across sentences, real words were used at the end of the sentences in the R condition. Upon the completion of the 3 sentences (word by word presentation, word duration 200 ms; stimulus onset asynchrony 500 ms), a prompt was shown requiring the participants to report the "hidden" word in the M+ and M− conditions or to produce a synonym or a semantic related word in the R condition. Guessing was encouraged. Participants were to say "don't know," if no meaning came to mind (note: English translation of Spanish materials, keeping the Spanish word order).

Materials and Methods

Pretests

Suitable sentences were selected after a pretest in 165 students of the University of Barcelona, all native speakers of Spanish. In this pretest, each sentence was presented in isolation with the final word missing and participants were required to complete the sentence with the first word that came to their mind and that fit well with the sentence. For each intended final word, 3 sentences were selected that differed regarding their contextual strength and thus gave a low, medium, and high rate of completions with the intended word (first sentence mean cloze probability for intended word was 6.1 ± 10.3% standard deviation [SD]; second sentence 28.5 ± 18.9%; third sentence 76.0 ± 17.7%). The materials generated from the pretest and used in the main experiment are given in Appendix 1 and 2.

ERP Learning Experiment

Twenty-four right-handed healthy native speakers of Spanish (mean age 21.7 ± 3.2 SD years; 18 women) participated after giving informed consent.

Sentence contexts were presented in random order with 65 triplets in each condition. Sentence contexts were rotated systematically over all conditions such that across the group of participants each sentence occurred equally often in each condition.

ERPs were recorded with tin electrodes mounted in an elastic cap and located at 29 standard positions (Fp1/2, F7/8, F5/6, F3/4, C3/4, C5/6, T7/8, Fpz, Fz, Cz, Pz, Cp3/4, Cp5/6, Tp7/8, P3/4, P7/8, O1/2). Electroencephalographic signals were rereferenced off-line to the mean of the activity at the 2 mastoid processes. Vertical eye movements were monitored with an electrode placed below the right eye referenced to the outer canthi of the right eye. The electrophysiological signals were filtered with a bandpass of 0.01–50 Hz (half-amplitude cutoffs) and digitized at a rate of 250 Hz. Trials on which base-to-peak electrooculogram (EOG) amplitude exceeded 50 μV, amplifier saturation occurred or the baseline shift exceeded 200 μV/s were automatically rejected off-line. The mean percentage of rejections was M = 17.7% (SD = 9.1).

ERPs were obtained for the terminal word separately for conditions and sentence position within a triplet (length 1024 ms, prestimulus baseline 100 ms). For illustrations, ERPs were low-pass filtered (cutoff frequency 8 Hz). Brain potentials were quantified by a mean amplitude measure (time window 300–500 ms) at different electrode locations. First, data were subjected to and omnibus repeated measures analysis of variance (ANOVA) with factors condition (R, M+, M–), sentence position (first, second, third), and electrode site (15 selected electrode locations: midline positions Fz, Cz, Pz plus F7, F3, F4, F8, T3, C3, C4, T4, T5, P3, P4, T6). Second, additional pairwise ANOVAs were carried out to assess differences between conditions at the midline positions, where amplitude differences were maximal. Third, in order to further analyze significant interactions that appeared in the omnibus ANOVA between the experimental factors (condition and sentence position) and electrode, 12 of the 15 electrodes were used for topographical analysis. The 12 selected electrodes (F7, F3, F4, F8, T3, C3, C4, T4, T5, P3, P4, T6) were divided to yield 3 factors: anteriority (anterior, central, posterior), laterality (parasagittal and temporal), and hemisphere (right and left). For all statistical effects involving two or more degrees of freedom in the numerator, the Greenhouse–Geisser epsilon was used to correct possible violations of the sphericity assumption. The exact P value after correction will be reported in conjunction with the original degrees of freedom. Tests involving electrode × condition interactions were carried out on data subjected to a vector normalization procedure (McCarthy and Wood 1985). Topographic maps were created using spherical spline interpolation and current source density (CSD).

Self-paced Reading Experiment

Eighteen volunteers (mean age 20.9 ± 1.8 years; 14 women) that did not partake in any of the other studies viewed 12 sentence triplets per experimental condition (R, M+, M–) in a randomized order and rotated across participants as in the first ERP experiment. The entire sentence was presented on the video screen with each letter replaced by the letter X. By pressing a key, the first word was revealed and could be read. Upon the next key press, this word was replaced by Xs again and the next word was rendered readable. Thus, reading times for each word were logged.

The use of this noncumulative moving-window methodology (Mitchell 1984) ensures that the participants read each word carefully in order to understand the meaning of the sentence. After the presentation of each context, a prompt was shown requiring the participants to write the "hidden" word in the M+ and M– conditions when possible and to produce a synonym or a semantic related word in the R condition.

ERP Generalization Experiment

Twenty new right-handed healthy native speakers of Spanish (mean age 21.5 ± 2.1 years; 16 women) participated.

Materials from the first experiment were used. Now, each stimulus list was divided into 8 sublists comprising 8 trials per condition (R, M+, M–) and 8 filler trials. Filler word sentences were included to equate the probability of real word and novel words at the end of the sentences. Filler sentences had the same structure as R conditions (3 sentences and ascending cloze probability). This condition was not included in the analysis because it was not rotated across the different scenarios.

After each learning block, the generalization experiment was presented. "Related" and "unrelated" word pairs were created for the novel words (only M+ condition) as well as for the real words from the R condition. Novel words from the M– condition were not presented. Novel words from the preceding block were presented twice, once prior to their real-word counterpart (related) and once prior to a real word that corresponded to a different novel item (unrelated). Trial order was counterbalanced across participants, such that half of them were first exposed to the related pair of a particular novel word, whereas the other half first saw the unrelated pair. For the real-word condition, the same logic was applied, but in this case, the second words of each pair were either synonyms or close semantic associates. Stimulus duration was 200 ms, and the stimulus onset asynchrony between the prime and target word was 500 ms. The intertrial interval between word pairs was varied randomly between 1 and 2 s. Participants pressed one button for related second words and another button for unrelated second words (see Table 2 for examples).

Amplifier settings and data processing was carried out as in the first ERP experiment. The relatedness effect was assessed by a mean amplitude measures at 2 different time windows (300–500 and 500–700 ms) at 15 electrode locations (Fz, Cz, Pz, F7, F3, F4, F8, T3, C3, C4, T4, T5, P3, P4, T6). These data were subjected to a repeated measures ANOVA including trial type (real-word vs. novel-word decisions), relatedness (related vs. unrelated), and electrode site (15 levels) as factors. To further analyze the significant interactions between experimental factors (trial type and relatedness) and electrode which appeared in this ANOVA, an additional analysis using the 12 lateral sites (F7, F3, F4, F8, T3, C3, C4, T4, T5, P3, P4, T6) assigned to 3 topographical factors and employing vector normalization was conducted (see Materials and Methods of first ERP experiment for details). In addition, pairwise comparisons between ERPs from related and unrelated trials were carried out separately for the novel- and real-word conditions in time intervals 300–500 and 500–700 ms. The unrelated minus related difference waveforms were subjected to a digital high-pass filter (1 Hz half-amplitude cutoff) to neutralize slow drifts.

Results

ERP Learning Study

Brain potentials to the terminal words of the first sentence of a triplet showed a larger negativity at posterior sites for real words from the R condition compared with both M+ and M– novel-word conditions (Figs 1 and 2, upper part). This negativity is an instance of the N400 component of the ERP that is thought to index the semantic integration of a word within the current context (Kutas and Hillyard 1984; Brown and Hagoort 1993; Kutas and Federmeier 2000). The scalp distribution of this component (see Fig. 2, left maps) showed a posterior distribution (difference waveform, R minus M+ or R minus M–). For the second sentence, brain potentials to novel words in the M+ condition were different from those presented in the M– condition between 250 and 550 ms. At the end of the third sentence, the ERPs from M+ and R conditions were indistinguishable and both were clearly different from M–, in particular at central and posterior locations.

The results of the omnibus ANOVA (mean amplitude 300–500 ms, 15 electrode locations) revealed a main effect of condition ($F_{2,46} = 10.71$, $P < 0.001$), sentence position ($F_{2,46} = 3.5$, $P < 0.05$), and a significant condition by sentence interaction ($F_{4,92} = 2.9$, $P < 0.025$). All the remaining interactions were significant (condition by electrode, $F_{28,644} = 10.7$, $P < 0.001$; sentence position by electrode $F_{28,644} = 5.8$, $P < 0.001$; condition × sentence × electrode $F_{56,1288} = 1.6$, $P < 0.01$). The main effects observed in the omnibus ANOVA were followed up by pairwise comparisons at midline locations (Fz, Cz, and Pz) of the conditions for each sentence. The results are summarized in Table 3 (see also Fig. 2, upper part) and corroborate the visual inspection of the ERPs. When novel words in the M+ condition were contrasted with M–, a significant difference appeared already at the second sentence with the M+/M– difference increasing further for the third sentence. Notice that the topography of the difference waveform comparing M+ minus M– at the end of the third sentence (see Fig. 2, right maps) shows also a standard N400 posterior right central distribution. No differences between R and M+ were present for the third sentence.

In order to decompose the condition × sentence × electrode interaction observed in the omnibus ANOVA, a topographical analysis using vector-normalized data was carried out as specified in Materials and Methods. Main effects of condition ($F_{2,46} = 10.7$, $P < 0.001$) and sentence position ($F_{2,46} = 4.9$, $P < 0.023$) as well as the interaction between condition and sentence position ($F_{4,92} = 2.7$, $P < 0.05$) were preserved. A significant interaction between condition and hemisphere was observed ($F_{2,46} = 5.8$, $P < 0.005$), which reflected the larger negativity over the left hemisphere for R words when compared with M+ and M– conditions (see also pairwise comparisons in Table 4). The significant condition × anteriority interaction ($F_{4,92} = 22.8$, $P < 0.001$) was due to the fact that R words showed a different distribution than both M+ and M– words (see Table 4; mean amplitude in μV at frontal, central, and parietal locations, M+: 0.28, 0.83, 1.92; M–: 1.1, 1.6, 2.7; R: 1.1, 1.04, 1.3). Finally, there was also a condition × laterality interaction ($F_{2,46} = 9.05$, $P < 0.001$; Table 4).

We also observed interactions between sentence position and anteriority ($F_{4,92} = 22.8$, $P < 0.001$; see also Table 4) as well as condition × sentence position × laterality ($F_{4,92} = 2.9$, $P < 0.031$)

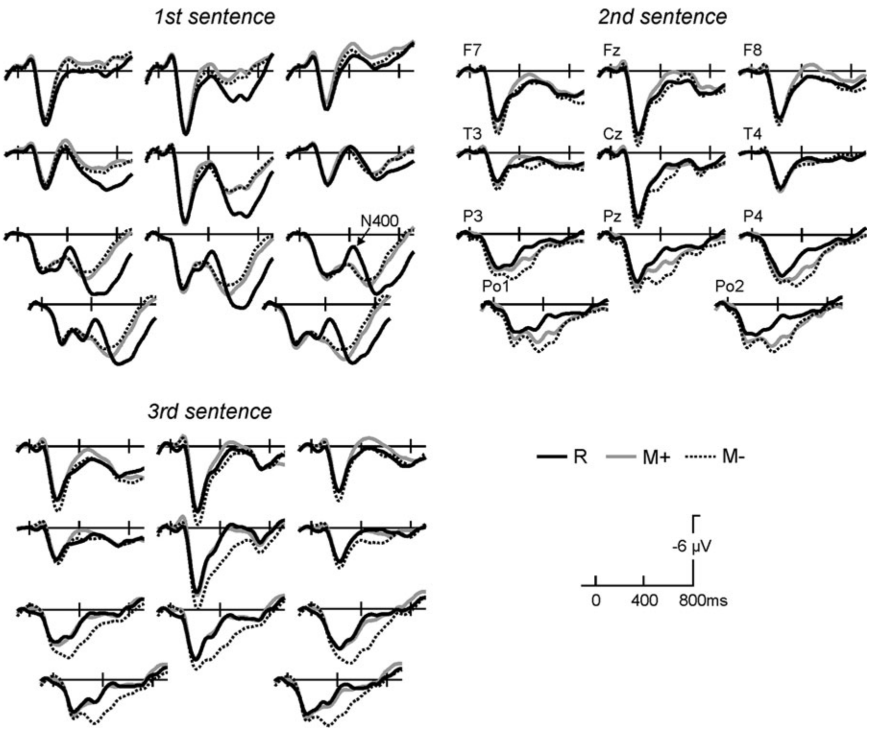

Figure 1. Group average ERPs to the terminal word show marked differences between conditions. For the first sentences, terminal words from the R condition were associated with a phasic negativity (N400) over posterior sites, indexing semantic integration. This is not seen in the M+ and M− conditions. For the second sentence, the brain potentials clearly differentiated between the 3 conditions with the M+ condition lying in-between R and M−. For the third sentence, M+ and R conditions are virtually indistinguishable.

and condition × sentence position × laterality × anteriority interactions ($F_{8,184} = 2.4$, $P < 0.041$; see also Table 4).

Reading Time Study

For the M+ condition, responses were considered correct when subjects reported the exact target word intended by the experimenters or a very closely related word. The overall meaning extraction in this experiment was 91.2% in the M+ condition with the majority of the responses being intended target words. In the case of R condition, subjects were asked to produce a synonym or a semantically related word. Responses would have been considered "incorrect," if the response did not have a semantic relation with the final word. Such responses did not occur. On average, the 18 subjects used 2.8 different answers for each word in the R condition. The pattern of reading times illustrated in Figure 3 suggests that participants attempted to extract a possible meaning in the M− condition even for the third sentence. In the first sentence, reading times for the terminal word were shortest in the R condition (see Table 5), whereas M+ and M− conditions did not differ. Novel-word conditions showed marked differences for the second and third sentences with reading times for terminal words in the M− condition showing a linear increase (sentence position main effect, $F_{2,17} = 18.5$, $P < 0.001$). Such an increase was not present in the other 2 conditions (M+: $F = 1.17$; R: $F = 1.5$). These results suggest that 1) in the M+ condition, the meaning of the novel words had been inferred using contextual learning and that 2) volunteers did not "give up" in the M− condition.

ERP Generalization Experiment

Button press responses for word pairs from the M+ learning conditions were correct in 69 ± 11.1% (SD) for related and 67 ± 14.1% for unrelated pairs. Thus, a moderate degree of word learning took place in the present experiment. Expectedly, a larger percentage of correct responses was obtained for related (90 ± 5.1%) and unrelated (95 ± 3.8%) pairs in the real-word condition ($F_{1,19} = 200$, $P < 0.001$). Decisions in the real-word condition were faster (827 ± 124 vs. 989 ± 130 ms; $F_{1,19} = 120$, $P < 0.001$). Decisions for related pairs were slower in both conditions (novel word: related 997 ± 129, unrelated 981 ± 132 ms; real word: related 839 ± 124, unrelated 815 ± 126 ms, $F_{1,19} = 4.02$, $P < 0.055$). There was no interaction between relatedness and condition ($F < 1$).

Inspection of the ERPs (Fig. 4) shows that the N400 component was reduced for second words of related pairs not only in the real-word condition but also in the novel-word condition. Thus, novel words from the M+ condition facilitated semantic processing of their corresponding real-word counterparts. Statistically, a relatedness effect was seen between 300–500 and 500–700 ms ($F_{1,19} = 17.3$, $P < 0.001$ and $F = 5.9$, $P < 0.025$, respectively). Pairwise comparisons showed that this effect was significant only during the first time window for real words and in both time windows for the novel words (see Table 6). A condition main effect was only observed in the second time window ($F_{1,19} = 5.17$, $P < 0.034$) and no interaction between condition and relatedness was found.

Topographic mapping of the N400 effect (Fig. 5*B*) showed a typical right posterior central maximum for the real-word control condition, which has been reported previously (Kutas and Hillyard 1989; Kutas and Federmeier 2000). This distribution has been related to neural generators in the left middle temporal and inferior frontal regions that support the integration of meaning using multiple sensory modalities and knowledge domains (Halgren et al. 2002). Indeed, CSD mapping (Fig. 5*C*, bottom left) revealed a temporal source–sink configuration.

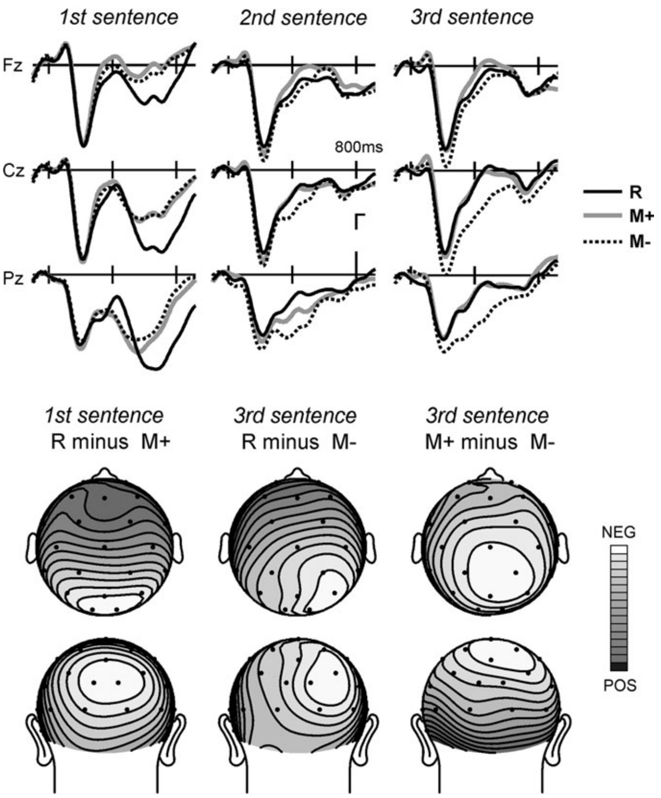

Figure 2. Grand average ERPs to the terminal words of the first experiment (midline locations, Fz, Cz, Pz). The topographic isovoltage maps (spherical spline interpolation) show the scalp distribution of the differences between conditions. Maps depict the mean amplitude in a 50-ms time window centered upon the peak of the difference waveform (in all cases 425 ms; relative scaling is used): R minus M+ comparison, minimum/maximum values, $-1.85/0.66$ μV; R minus M−, $-1.8/0.55$ μV; M+ minus M−, $-2.79/0.48$ μV.

Table 2
An example of the experimental conditions used in the second ERP experiment

Condition	Novel-word learning		Real word	
	Prime (new word)	Target (hidden word)	Prime (word)	Target (semantic relation)
Related	Ateloso	Tomate (tomato)	Autobús (bus)	Tranvía (tram)
	Vatesa	Nevera (fridge)	Cuchillo (knife)	Navaja (clasp knife)
Unrelated	Ateloso	Nevera	Autobús	Navaja
	Vatesa	Tomate	Cuchillo	Tranvía

By contrast, the relatedness effect in the novel-word condition showed a frontocentral distribution reveals and the CSD map revealed a frontal source-sink configuration (Fig. 5*C*, bottom right). Statistically, a second set of ANOVAs, using vector-normalized data, showed that the scalp distribution of the relatedness effect was different for real and novel words in the 300- to 500-ms time window (condition × relatedness × hemisphere, $F_{1,19} = 10.8$, $P < 0.004$). In addition, significant interactions were found for relatedness × hemisphere ($F_{1,14} = 15.8$, $P < 0.001$), relatedness by laterality ($F_{1,19} = 23.7$, $P < 0.001$), relatedness × hemisphere × anteriority ($F_{2,38} = 3.6$, $P < 0.016$). These interactions reflected the fact that the priming effect was largest at right parasagittal and central posterior locations. Further, condition × hemisphere ($F_{1,19} = 8.8$, $P < 0.008$) and condition × hemisphere × anteriority ($F_{2,38} = 7.04$, $P < 0.0028$) interactions reflected different scalp distributions of the ERPs in the novel- and real-word conditions. A very similar pattern of topographical effects was observed for the second time window evaluated (500–700 ms).

Table 3
ERP learning experiment: *F*-values from pairwise ANOVAs comparing the different conditions at the midline electrode locations (Fz, Cz, and Pz)

300–500 (ms)		First sentence	Second sentence	Third sentence
M+ versus M−	Condition	NS	7.5**	33.3***
	Cond × E	NS	NS	NS
M+ versus R	Condition	NS	NS	NS
	Cond × E	4.5*	6.6**	NS
M− versus R	Condition	NS	6.5*	12.3*
	Cond × E	NS	5.8**	4.9*

Note: Degrees of freedom: condition (cond, 1,23) and interaction condition × electrode (cond × E, 2,46). NS, not significant.
*$P < 0.05$.
**$P < 0.01$.
***$P < 0.001$.

It is important to note that the peak latency of the N400, determined in the unrelated minus related difference waveforms, was delayed by 152 ms in the novel-word condition (Fig. 5*A*; peak latency in time window 300–900 ms; $F_{1,19} = 15.1$, $P < 0.001$). This latency difference paralleled the differences observed in mean reaction time for real-word and novel-word target decisions (827 ± 124 (SD) vs. 989 ± 130 ms, respectively; $F_{1,19} = 120$, $P < 0.001$).

Discussion

To our knowledge, this is the first ERP study addressing the process of meaning acquisition from context in real time. Using the contextual constraints of the sentences, a meaning is mapped onto the novel word. The change of the brain potential signature for novel words from the M+ condition toward that of the real words over the sentence triplets qualifies as a neural correlate of the online acquisition of the meaning of a novel word extracted from a context. Importantly, participants were able to discern what semantic concept the new word was referring to using only 3 sentences that included the new word at the end of each sentence.

Moreover, as shown by the second ERP generalization experiment, learned words as well as real words lead to reductions of ERP amplitude to immediately following matching real words. This amplitude reduction might signal either the activation of the concept associated to the (learned) novel word at this learning stage or the activation of the associated (hidden) word. This latter possibility is corroborated by behavioral investigations addressing the learning of words in a second language (Kroll and Stewart 1994), which suggest that in the initial learning phases the link between a novel word and the corresponding word in the first language is stronger than the link between the novel word and the concept it denotes. With the repeated use of the new word, the conceptual link might be reinforced and speakers might be able to use this path freely in order to comprehend and produce words without having to rely on the lexical association between the novel word and the word in the first language. Further studies are needed in order to understand the neural mechanisms involved in the consolidation of the lexical and semantic links of the novel words and their brain representations.

Closer inspection of the effect in the generalization experiment reveals that it is both delayed and associated with

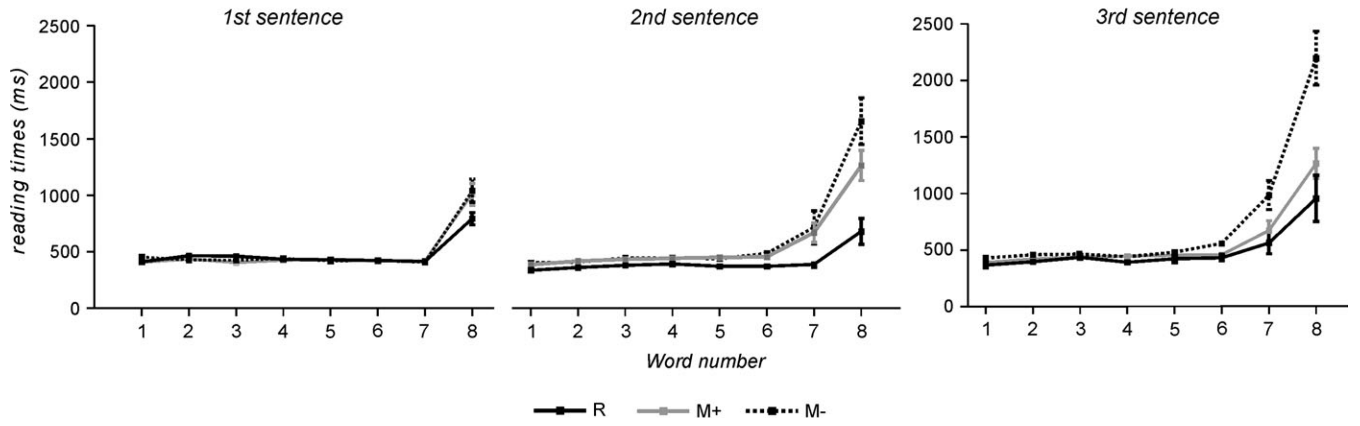

Figure 3. Mean self-paced reading times ± standard error of mean in the self-paced reading experiment for different word positions and sentences. New words were presented at the end of each sentence in the new-word conditions. Notice that new words in the M+ (meaning) and M− (no meaning) conditions began to differ from the R condition along the second sentence. In the third sentence, a clear differentiation between new-word conditions can be observed.

Table 4

ERP learning experiment: pairwise ANOVAs comparing the different conditions and including topographical factors: laterality, hemisphere, anteriority

		R versus M+		M + versus M−		M− versus R+	
	df	*F* =	*P* <	*F* =	*P* <	*F* =	*P* <
Condition (C)	1,23			28.9	0.001	10.4	0.004
Sentence position (S)	2,46			7.1	0.005	4.7	0.014
C × S	2,46			4.5	0.018	3.6	0.04
C × lat	1,23			19.05	0.001	14.1	0.001
C × S × lat	2,46			6.5	0.004		
C × hem	1,23	5.4	0.029			11.4	0.003
C × ant	2,46	28.7	0.001			2.5	0.001
S × ant	4,92	4.92	0.001	8.6	0.001	9.6	0.001
C × S × lat × ant	4,92					3.8	0.007

Note: laterality, lat; hemisphere, hem; anteriority, ant; df, degrees of freedom.

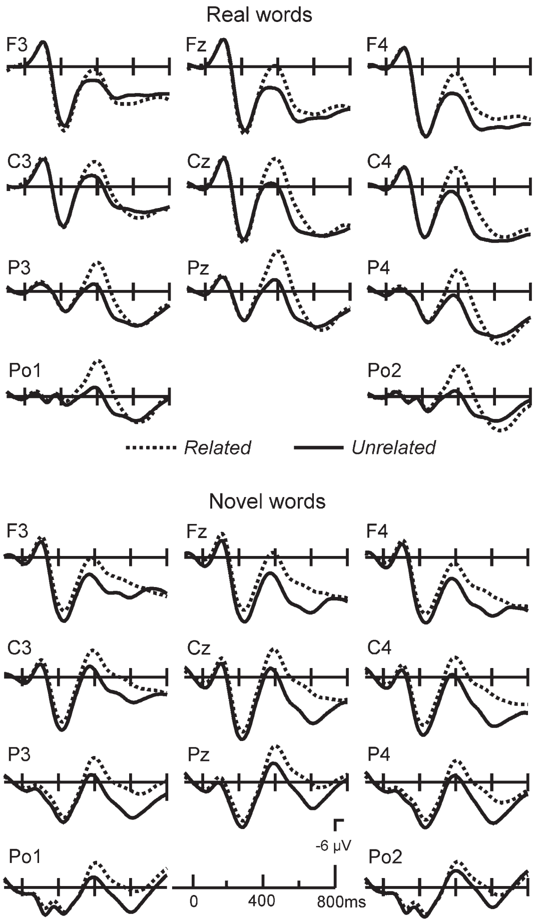

Figure 4. Grand average brain potentials for target words in the generalization experiment. Brain potentials to the second word of a pair varied as a function of their relation to the first word (semantically related or unrelated). Unrelated words showed a more negative course from 250 ms onward in both the novel-word and the real-word conditions.

a different scalp topography in the novel-word compared with real-word condition. Whereas the relatedness effect can be ascribed to a temporal source–sink configuration in the real-word condition, a frontal source–sink ensemble was seen in the novel-word condition most probably suggesting the involvement of prefrontal regions. This corresponds nicely to recent neuroimaging studies of semantic priming that have shown suppressed activity in the inferior frontal gyrus and in the middle temporal regions for semantically related words (Kotz et al. 2002; Matsumoto et al. 2005).

Although ERPs allow to localize their neural sources only with some uncertainty, topographical differences as the ones evidenced here permit to conclude that a different neural network is recruited in the real-word and novel-word conditions. One of the explanations for the topographical differences observed in the generalization experiment between novel and real words is that in the former the preexisting associative relations are still weaker and, therefore, an increase in cognitive control might be required in order to guide semantic knowledge retrieval and selection. This finding would predict that second-language learning will require the involvement of cognitive control mechanisms that regulate the differential strengths and levels of activation of the different representations during the learning process (Rodriguez-Fornells et al. 2006). In contrast, stable associative links exist in the real-word condition, which should render retrieval attempts more automatic and less dependent on cognitive control processes. Thus, we propose that retrieval of the meaning of a novel word enlists a prefrontal network driven by retrieval effort and monitoring demands. It remains to be shown whether consolidation of the novel words via further practice and use in multiple contexts and the resulting direct

Table 5
Self-paced reading experiment: pairwise t-test comparisons of the reading times for the terminal words ($n = 18$)

	First sentence	Second sentence	Third sentence
M+ versus M−	NS	−2.7*	−3.3**
M+ versus R	3.1**	3.3**	NS
M− versus R	2.8*	3.7**	3.7**

Note: Degrees of freedom for the t-tests 17. NS, not significant.
*$P < 0.05$.
**$P < 0.01$.

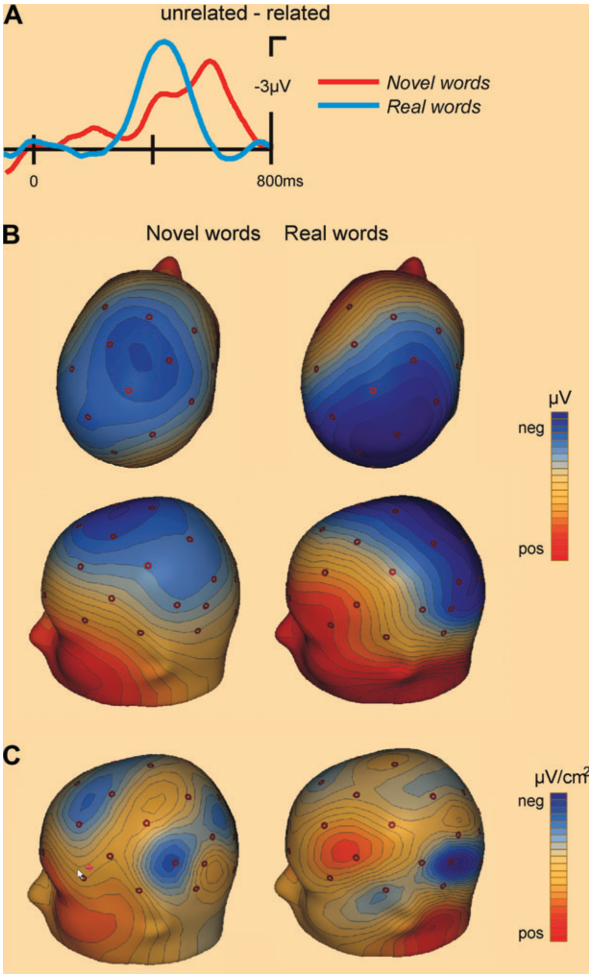

Figure 5. Unrelated minus related difference waveforms (right central parietal location, Cp2) show a negativity for both real-word and novel-word conditions. (*B*) The scalp distribution of the relatedness (difference waveform) effect at the peak value shows a right parietal maximum in the real-word condition, whereas the peak activity is observed over frontocentral brain regions in the novel-word condition. Isovoltage maps were created using spherical spline interpolation. (*C*) CSD maps at the same time points and for both conditions.

Table 6
Results of the pairwise comparison of unrelated versus related target words (mean amplitudes in the corresponding intervals at 15 electrode locations) at 2 different time windows

	300–500 (ms)	500–700 (ms)
Relatedness effect		
New words	**7.03***	**13.7****
Real words	**23.9*****	0.09
Priming × electrode		
New words	**3.00****	**3.67****
Real words	**7.15*****	**2.54****

Note: Bold numbers underscore significant effects. Degrees of freedom: relatedness (1,19) and the interaction between priming and electrode (14,266). Interaction values have been previously vector normalized.
*$P < 0.05$.
**$P < 0.01$.
***$P < 0.001$.

access of the novel word to its concept would abolish the brain potential differences between novel and real words.

To what extent can these findings be generalized to more natural situations, for example, adults acquiring a second language or children learning their first (Bloom 2000)? A previous study found that native speakers of English, after only 14 h of exposition to a new language (French), showed an N400 effect in the second language even when performance was still at chance level in a word/nonword decision task (McLaughlin et al. 2004). Also, an N400 increase has been observed when adults tried to segment words from artificial language streams (Sanders et al. 2002; Cunillera et al. 2006). Clearly, the current experiment greatly restricted the information available to the learner. Learning in the real world often entails some sophisticated mind reading of the speaker's intentions (Tomasello and Akhtar 1995; Bloom 2000, 2002) in addition to linguistic input to aid word-to-meaning mapping. Ultimately, these different information types may engage very similar learning processes, and the current experimental paradigm seems suited to study word learning in different populations and with different kinds of information used for the assignment of words to meaning.

Notes

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Appendix I: Novel Words, Corresponding Spanish Words (English Translation)

Alusira, medusa (jellyfish); ambil, interruptor (light switch); anclana, bicicleta (bicycle); añiro, problema (problem); arniso, horno (oven); astiro, cenicero (ashtray); ateloso, tomate (tomato); bacono, pantalón (trousers); balicon, metro (underground); banita, nube (cloud); belto, pájaro (bird); beteso, coche (car); bilsa, manzana (apple); bina, serpiente (snake); bisaco, plátano (banana); biteco, ajo (garlic); buino, horóscopo (horoscope); cajuro, sorteo (draw); califiro, aeropuerto (airport); campeto, biquini (bikini); catela, mosca (fly); cema, baile (dance); cemaco, ascensor (lift); cerino, barco (boat); ceteno, cinturón (belt); chacorena, guitarra (guitar); cija, llave (key); cilso, pan (bread); cirana, uña (nail); cireto, saxofón (saxophone); cirito, parchís (parcheesi); clisea, montaña (mountain); clito, oso (bear); cratino, buzón (mailbox); culiseo, avestruz (ostrich); dalina, ciudad (city); desala, isla (island); dico, lazo (knot); dilera, tarjeta (target); dileto, autobús (bus); dirita, hormiga (ant); dito, hacha (axe), dodero, café (coffee); ectero, martillo (hammer); endole, avión (plane); enlufe, tenedor (fork); eritino, chocolate (chocolate); escrayo, payaso (clown); esreso, plato (dish); eteiso, salero (salt shaker); fagarino, pegamento (glue); faleto, semáforo (traffic light); falito, árbol (tree); falliro, grifo (tap); farena, película (movie); ferieto, mapa (map); fimeta, toalla (towel); fisena, vacuna (vaccination); fiteto, periódico (newspaper); fleta, bufanda (scraf); flipeto, casco (helmet); futa, mancha (spot); gareta, lavadora (washing machine); gerias, tijeras (scissors); gitero, teléfono (phone); gopeta, rosa (rose); gurato, hotel (hotel); hareta, pila (battery); helita, mano (hand); histana, almohada (pillow); hiteco, móvil (mobile phone); ilero, regalo (present); imbra, flor (flower); intrial, helicóptero (helicopter); iprita, pirámide (pyramide); jarilo, elefante (elephant); jarina, canción (song); laena, peluquería (hairdresser's); laeta, grapadora (stapler); lecato, guante (glove); lepito, cuchillo (knife); lertico, pez (fish); lesico, lápiz (pencil); liantro, dinosaurio (dinosaur); licana, estrella (star); licata, raqueta (racket); limino, colegio (school); lineto, gato (cat); liñero, despertador (alarm clock); lizeno, chiste (joke); logarino, otoño (fall); lopero, satélite (satellite); lucata, ducha (shower); luerca, pistola (gun); macito, diente (thooth); malinro, queso (cheese); malisiro, calcetín (sock); mecrallo, abrigo (coat); metico, ejercicio (exercise); milso, ojo (eye); miluto, termómetro (thermometer); misaleta, agua (water); muneiera, autopista (motorway); nagato, bigote (moustache); nalposa, naranja (orange); niepa, uva (grape); nilanera, sábana (sheet); nilata, casa (house); nileca, bombilla (bulb); nilopo, taxi (taxi); nocanal, globo (balloon); nosa, caja (box); oerelo, anillo (ring); oleta, plancha (iron); olieto, fútbol (football); oprisa, cabra (goat); ovisera, panadería (baker); paceto, río (river); pano, cubo (bin); patora, campana (bell); pecua, mariposa (butterfly); peltro, brazo (arm); penrota, silla (chair); petira, cama (bed); pieta, abeja (bee); pilso, bolígrafo (pen); pireje, cigarro (cigarrette); pireliso, médico (doctor); pirter, collar (necklace); pitsal, cine (cinema); puca, maleta (suitcase); quiro, corazón (heart); ralao, color (colour); recola, taza (cup); remoca, pierna (leg); respo, oído (ear); ricata, paella (paella); rinaca, patata (potatoe); rinilo, padre (father); ristro, dedo (finger); riteto, esquí (skiing); sabeta, lámpara (lamp); saceyo, televisor (television); safena, cocina (kitchen); saleca, vaca (cow); saleno, león (lion); sendelio, espejo (mirror); sileca, libreta (notebook); silera, vela (candle); silino, zapato (shoe); siltra, aguja (neddle); siptio, sombrero (hat); sitera, puerta (door); sito, pollo (chicken); sofireto, restaurante (restaurant); sogaro, pastel (cake); solefa, bandera (flag); sufeto, calendario (calendar); sulico, amigo (friend); tacela, luna (moon); tacetelo, ordenador (computer); talino, aceite (oil); tareta, matrícula (licence plate); tarra, piscina (swimming pool); tastera, zanahoria (carrot); tealena, serie (sit com); telepo, libro (book); tepa, botella (bottle); tepoto, canguro (kangaroo); tesa, leche (milk); tezo, botón (botton); ticha, pelota (ball); tilapo, reloj (clock); tileco, vestido (dress); tilena, flecha (arrow); tilina, nariz (nose); tombro, bolso (handbag); traum, bocadillo (sandwich); trepto, cuadro (painting); trilebo, sofá (sofa); tristero, paraguas (umbrella); tulsas, gafas (glasses); ulina, gota (drop); urtilera, iglesia (church); utileco, bar (bar); valireta, escalera (stairs); valirino, girasol (sunflower); vatesa, nevera (fridge); viato, azúcar (sugar); vieleto, mensaje (message); vileta, ventana (window); yalito, microondas (microwaves oven); yutiro, fuego (fire); zilatera, calculadora (calculator), zineta, cebolla (onion).

Appendix II: Five Examples of the Sentences Constructed (English Translation of Sentences in Brackets, Note: Word Order from the Original Spanish Has Been Preserved)

New-Word Meaning Condition

A. Cada día Luís va al colegio en anclana./Se rompió el brazo cayendo de la anclana./Tengo que cambiar los pedales de la anclana. (Everyday, Luís goes to the school on his __./She broke her arm when she fell from the __./I have to change the pedals of my __.)

B. Me gusta pasar el rato con el fiteto/Supe de aquel empleo a través del fiteto/Pablo cada día compra y lee el fiteto (I enjoy my time reading the __/I knew about the job thanks to the __/Everyday, Pablo, buys and reads the __.)

C. El gran sueño de Carolina es ser pireliso/Al llegar había muchísima gente esperando al pireliso/Me duele mucho la barriga, iré al pireliso (Carolina is dreaming to become a __/When we arrived, there were a lot of people waiting for the __/I have a bad stomach-ache, I should go to the __.)

D. Los padres de Mario tienen un nuevo cerino./Este verano Carlos tendrá que viajar en cerino./Como adora navegar se ha comprado un cerino. (Mario's parents have a new __./This summer Carlos is going to enjoy his new __./Because he loves sailing, he bought a __.)

E. Es muy sano comer a diario una bilsa./De postre Paula se ha comido una bilsa./Los expulsaron del paraíso por comer una bilsa. (It is healthy to eat a __./For dessert, Paula ate a __./They were expelled from the garden of Eden for eating an __.)

New-Word No-Meaning Condition

A. A Carmen le regalaron un juego de nilaneras./Al caerse Juan se lastimó en una nilanera./No puede oler nada, tiene tapada la nilanera. (They gave Carmen a set of __./When Juan fell, he hurt his __./He can not smell anything, he has stuffed __.).

B. Me gusta el ruido metálico de las cijas./De este paisaje podría hacerse una buena cija./La miel la tenemos gracias a las cijas. (I love the metallic noise of __./From this view, it looks like a good __./We have honey thanks to the __.).

C. Por su cumpleaños Juan le regaló un flipeto./Juan se disfrazó poniéndose por encima un flipeto./La fruta típica de Canarias es el flipeto. (For his birthday Juan gave him a __./Juan dressed up with a __./The typical fruit from The Canary Islands is the __.).

D. Te has dejado en el coche el ferieto./Antes de comértelo quítale la piel al ferieto./Vigila, te puedes quemar si juegas con ferieto. (In the car, you forgot the __./Before eating it, take off the peel of the __./ Take care, you can be burnt if play with __.).

E. La policía no pudo nunca encontrar la luerca./A Lucía le encanta la hamburguesa con luerca./José, a tu cama toca cambiarle las luercas. (The police could not find the __./Lucia loves eating hamburgers with __./José, your bed needs a change of __.).

Real-Word Condition

A. Le ha regalado a su hijo una pelota./Es imposible jugar si no conseguimos una pelota./El portero fue capaz de atrapar la pelota. (He gave his son a ball./It is impossible to play if we don't have a ball./The goalkeeper was able to catch the ball.)

B. El insecto que menos gusta es la mosca./Con este insecticida no podrás matar la mosca./La Tsé-tsé, es un tipo especial de mosca. (The most disgusting insect is the fly./With this insecticide you can't kill the fly./The Tsetse is a special kind of fly.)

C. Has olvidado poner en la mesa mi cuchillo./En la cocina no he encontrado ningún cuchillo./Se ha cortado el dedo con un cuchillo. (You have forgotten to put on the table my knife./In the kitchen, I haven't found a knife./She cut her finger with a knife.)

D. Esta mañana he ido a comprar unas gafas/No me gusta nada tener que usar gafas./Para leer o ver la televisión necesito gafas. (This morning, I bought new glasses./I don't like having to wear glasses./ For reading or watching television I need glasses.)

E. En medio de la carretera había una vaca./En toda la granja sólo hay una vaca./El granjero atendió el parto de una vaca. (In the middle of the road there was a cow./In the whole farm there is only one cow./ The farmer attended the birth of a cow.)

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