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How negation is understood: Evidence from the visual world paradigm

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ABSTRACT

This paper explores how negation (e.g., *the figure is not red*) is understood using the visual world paradigm. Our hypothesis is that people will switch to the alternative affirmative (e.g., a green figure) whenever possible, but will be able to maintain the negated argument (e.g., a non-red figure) when needed. To test this, we presented either a specific verbal context (binary: *the figure could be red or green*) or an unspecified verbal context (multary: *the figure could be red or green or yellow or blue*). Then, affirmative and negative sentences (e.g., *the figure is (not) red*) were heard while four figures were shown on the screen and eye movements were monitored. We found that people shifted their visual attention toward the alternative in the binary context, but focused on the negated argument in the multary context. Our findings corroborated our hypothesis and shed light on two issues that are currently under debate about how negation is represented and processed. Regarding representation, our results support the ideas that (1) the negative operator plays a role in the mental representation, and consequently a symbolic representation of negation is possible, and (2) it is not necessary to use a two-step process to represent and understand negation.

Introduction

Negation is an important element of language with considerable cognitive consequences. It changes the truth value of assertions (reverting true to false and vice versa), and, interestingly, it does so by representing the world in a way that deviates from what is simply the case. An affirmative sentence like "the car is red" refers to the world in a direct way, in that it describes an entity (a car) that has the property of being colored red. Yet, the simple addition of the word "not" to the same sentence (e.g., "the car is not red") comes to refer to something profoundly different: a world in which it is not the case that the property of being colored red applies to the entity referred to in the sentence. In the present study, we make use of the visual world paradigm to explore how people comprehend and represent the world from negations. In particular, we focus on the two issues that are currently the subject of much debate in negation comprehension: (1) what role in negation comprehension, if any, does the negative operator play in the mental representation encoded by hearers, and (2) how many representational steps are triggered, and necessary, to understand a negative?

Theories about negation comprehension

Cognitive accounts of negation can be analyzed in terms of two domains of divergence. First, they diverge with respect to the role given to the negation operator in the mental representation that becomes encoded during comprehension. One view is that the negative operator forms part of the mental representation of the world, as a 'mental

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tag' (Carpenter & Just, 1975; Clark & Chase, 1972; Trabasso, Rollins, & Shaughnessy, 1971). For others, in contrast, it is simply an element of discourse, which has no explicit representational correspondence in the mind (Barsalou, 1999, 2005, 2008, 2012; Glenberg, Meyer, & Lindem, 1987; Zwaan & Radvansky, 1998). The second source of disagreement between scholars concerns the processing dynamic that underlies negation comprehension. For some, two mental representations are always sequentially encoded during negative sentence comprehension, such that the processing of negation becomes characterized in the shift from one representation to another (Kaup, Lüdtke, & Zwaan, 2006). For example, shortly after reading a sentence like *'The door is not open'*, one would first encode a representation of an open door and then later encode a different, alternative representation (e.g., a closed door). For others, however, this shift between two mental representations is not obligatory, because either the mental representation of the negated content is enough to support the comprehension process (e.g., Clark & Chase, 1972) or because the representation of the alternative state of affairs occurs automatically, without having to represent the negated argument (Anderson, Huette, Matlock, & Spivey, 2010; Tian, Breheny, & Ferguson, 2010).

At least three representational accounts can be distinguished according to the above classification. First is the classical, propositional theory of negation, which holds both that negation is directly, mentally represented and that there are two ways of processing negative sentences during comprehension. One of these ways would involve the representation of the negated argument together with the negative operator (e.g., NOT[DOOR OPEN]), which is considered to suffice for comprehension (Carpenter & Just, 1975; Clark & Chase, 1972; Trabasso et al., 1971). The other way would involve the recoding of the negated argument into an alternative affirmative (e.g., NOT[DOOR OPEN] into AFF[DOOR CLOSED]). This theory does not currently enjoy much support among researchers, likely due to its overreliance on propositional representations. However, it is worth remarking that the two ways of processing negation that it proposes fit nicely with much of the extant evidence about negation processing (for a review, see Kaup et al., 2006).

On the opposite side of the propositional theory, we have the recently proposed two-step simulation theory, which is framed in the more general embodiment view. This theory rejects the idea that negation operators can figure in one's mental representation of a sentence. Instead, it suggests that negation comprehension depends on a process that uses solely mental representations that are completely grounded in sensorimotor experience. This process always begins with the simulation of the negated argument (e.g., an open door) and continues with the simulation of the alternative (e.g., a closed door). This theory holds that these two steps are mandatory for comprehension, even when the alternative is not available. In those cases, comprehenders might represent the negated argument that they will later reject to represent the alternative affirmative, although this simulation could be empty (Barsalou, 1999) or unspecified. For example, *the door is not blue* could well be simulated by representing a door of an unspecified color (Kaup, Zwaan, & Lüdtke, 2007). Within the framework of perceptual-simulation theories, it has been also proposed (Anderson et al., 2010) that rather than a two-step sequence of static images, negation would be represented by the derivative over time in a perceptual simulation.

Finally, somewhere in the middle between perceptual-simulation and propositional theories we find the Mental Model theory, or model theory for short (Johnson-Laird, 1983, 2006). This theory holds that many of the mental representations used during comprehension and reasoning are simulations (mental models) that do not directly represent the linguistic input. Nonetheless, it does not exclude the possibility that the human cognitive system can encode iconic and symbolic representations during comprehension. According to the model theory, individuals understand negation by simulating either the alternative affirmative or the negated argument while applying a symbol that represents negation (Khemlani, Orenes, & Johnson-Laird, 2012). Consider the following assertion: *the circle is not to the right of the triangle*. In order to understand this situation, model theory predicts that individuals will construct an iconic model of the corresponding affirmative assertion and then apply the negation symbol. The resulting model might look like this:

$$\neg\ \boxed{\triangle\ \bigcirc}$$

The symbol of negation (¬) does not mean that people represent negation like that. It is unknown how people represent negation. They may represent the iconic model with a superimposed cross or represent negation via a marker of falsity, as Clark and Chase (1972) proposed. What is clear is that the operator of negation can only be represented symbolically, thus individuals have to know that the symbol stands for negation, because nothing in the image could tell them that (Wittgenstein, 1953).

In sum, all theories agree that negation takes an argument and rejects it. The difference between the theories would be in the necessity of representing the alternative affirmative. If people represent the alternative to understand negation, the resulting representation is iconic, because negation is not represented explicitly, thus this finding supports the embodiment theory. However, if they represent just the negated argument, this representation should be symbolic, or at least not purely iconic, because a symbolic marker is needed to represent negation without swapping to the alternative. This latter finding would suggest that individuals are able to represent symbolic information.

The present study

The goal of the present study was to determine whether accessing the alternative affirmative is necessary to understand negation, or just one possibility. Our hypothesis is that the way in which individuals understand negation is modulated by the availability of the alternative affirmative. In other words, people could represent the alternative when it is available, such as in binary (or complementary) predicates: in the case of 'not odd', there is only one alternative, 'even' (Wason, 1961). However, when the alternative is not available, such as in multary predicates (e.g., blue-red-green-yellow), the correspondence with the alternative, unless it is obvious from the context, is not straightforward. As a consequence, people may represent the negated argument and the operator of negation explicitly. To test this hypothesis, we manipulated the availability of the alternative, presenting binary and multary contexts in a visual world paradigm experiment.

In this task, verbal and visual inputs are presented simultaneously while eye movements are recorded. Experiments have shown that when linguistic input matches visual input, the eyes will begin to move automatically towards the corresponding visual input (Cooper, 1974; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). These results suggest that it is the conceptual overlap between the word and the object that mediates between language and eye movements. These data on semantic relatedness rule out an account based solely on phonological overlap between the unfolding word and the names associated with the objects in the scene (Altmann, 2011). Eye movements are thus presumed to reflect interactions between linguistic and visual representations that occur at the level of conceptual representation (Salverda, Brown, & Tanenhaus, 2011).

In keeping with the above assumptions, it follows that when people are exposed to negative assertions in a visual world paradigm, they will look more frequently at the most active information in working memory. The advantage of the visual world paradigm for studying negation is that all the objects (whether or not they are related to the comprehension of the sentence) are displayed on the screen, and so people are free to turn their attention to whatever object is required for processing and representation. With respect to the timing of the display of the input, most of the paradigms applied thus far in research on negation have opted for using a discrete delay (150–250–500–750–1500 ms) between the sentences and the pictures (see Hasson & Glucksberg, 2006; Kaup et al., 2006; Lüdtke, Friedrich, De Filippis, & Kaup, 2008). The results suggest that negation is fully integrated into sentence meaning only at a later stage of the comprehension process (between 750 and 1500 ms). However, sentence comprehension should not take that long, and so it might be worthwhile to use another methodology to record what is happening in that lengthy period of time.

Using the visual world paradigm, we presented affirmative and negative sentences (e.g., *the figure was (not) red*) in the binary (e.g., *the figure could be red or green*) and multary contexts (e.g., *the figure could be red, or green, or blue, or yellow*) via a loudspeaker while four colored figures (e.g., yellow, blue, green, and red) were shown on the screen. One of the colors represented the negated argument (e.g., the red figure) while the others stood for the alternatives (e.g., the yellow, blue, and green figures). With this design, the participants (and not the researchers) were able to manage the pace of their comprehension, thus allowing us to determine the temporal course of negation. Also, our use of the visual world paradigm allowed us to determine what people were looking at when comprehending negative sentences: did they focus on the negated argument or the alternatives? In sum, the visual world paradigm has two advantages: one, it enables us to trace the time course of negation; and two, it allows us to know what people keep in mind through their visual attention.

Method

Participants

Thirty-one native Spanish speakers from the University of La Laguna, Tenerife (Spain), participated in the experiment in exchange for course credits. All of them had uncorrected vision or wore soft contact lenses or glasses.

Materials

Sixty-four experimental trials were presented to participants distributed in four conditions. For each trial, a different display with four colored figures was shown on the screen (see Fig. 1). These figures occupied distinct quadrants of the display and were always of different colors (yellow, blue, green and red). The same colors were used in all the experimental displays, but with the quadrant position counterbalanced. In contrast, the figures' shape (diamonds, triangles, circles, or squares) varied across displays, but were always the same for the four figures in each display. In other words, all figures were of different colors but an identical shape within trials, and of the same color but different shapes across trials.

The experimental conditions were generated from the combination of two spoken sentences, both presented via loudspeakers. In each trial, the first sentence established the verbal context, which was either binary (e.g., *the figure could be red or green* -translated as '*la figura puede ser roja o verde*') or multary (e.g., *the figure could be red, or green, or blue, or yellow* –translated as '*la figura puede ser roja, verde, azul, o amarilla*), and the second sentence was the target, which was referred to in either an affirmative (e.g., *the figure was red* -translated as '*la figura es roja*') or negative polarity form (e.g., *the figure was not red* - translated as '*la figura no es roja*'). The resulting conditions were hence: binary affirmative, binary negative, multary affirmative and multary negative. In total, there were 16 experimental trials per condition. For all trials, the target word was the color word mentioned in the second sentence. This target word established the onset from which the fixation time-course was analyzed.

In addition to the figure display, a written question was also shown on the screen at the end of each trial. This question involved the detection of the shape of the figures in the display (e.g., *were the figures circles?* – translated as '*¿eran las figuras círculos?*') and was unrelated to the spoken sentences, which always referred to the color. In this way, the impact of speech comprehension on fixations could be detached from the impact of the task goal.

Apparatus and procedure

Participants' eye movements were recorded at a rate of 500 Hz using an SR Research EyeLink II head-mounted

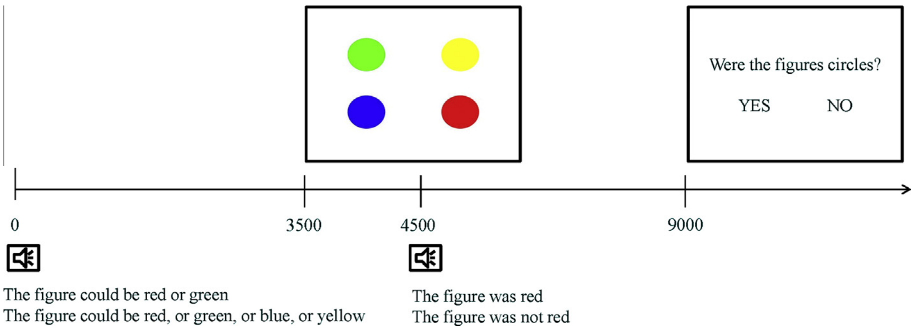

Fig. 1. Experiment procedure (the sentences have been translated from the Spanish).

eye-tracker connected to a 21-in. color CRT for visual stimulus presentation. Procedures were implemented in the SR Research Experiment Builder. Calibration and validation processes were carried out at the beginning of the experiment and repeated several times per session. Trials started with the display of a central fixation dot for drift correction (see Fig. 1) while participants listened to a verbal context sentence lasting 3500 ms. After that, a display with the four colored figures appeared for 5500 ms. The target sentence was delivered after one second of display preview, with the target word starting 1500 ms later for affirmatives, and 1600 ms later for negatives. The trial concluded with the appearance of the written question (e.g., *were the figures circles?*), to which participants had to answer either 'yes' or 'no', with each response being correct for half of the trials. We identify this question with a recognition task, because participants had to recognize the shape of the figures presented previously. There was a practice block before the experimental block. The trials of this block (eight in total) followed the same structure but used a different set of colors (gray, violet, brown and orange). The entire experiment lasted approximately 30 min.

It may be important to clarify here that participants were not asked to complete any specific task. Most experiments with eye-trackers include specific instructions to interact with the display (touching, clicking, or moving objects); our participants only had to listen to the sentences and answer the written question. They did not have to do anything on the screen, although they did have to look at it in order to answer the questions about shape of the figures correctly. In this sense, our study might be interpreted as exploring the sort of automatic, implicit processes of comprehension that have been evaluated in some previous sentence-picture studies that used either picture naming or probe recognition tasks instead of verification (e.g., Kaup et al., 2006; Tian et al., 2010).

Results

Behavioral data

Response accuracy and latency were both analyzed separately using two-way ANOVAs with verbal context and polarity as factors. The aim of these analyses was to test whether there was any influence of the spoken sentences on the recognition task. Accuracy analyses failed to show any significant sign of interference. In contrast, latency analyses did reveal that the response times were modulated by the spoken materials. Specifically, they showed that response latencies were slower after negative sentences (1288 ms; sd = 41) than after affirmatives (1242 ms; sd = 38; $F(1, 30) = 6.987$, $p = .013$, $\eta^2 = .189$), and were also slower after binary contexts (1282 ms; sd = 41) than after multary contexts (1248 ms; sd = 38; $F(1, 30) = 6.425$, $p = .017$, $\eta^2 = .173$). For affirmative (binary context: 1258 (224) ms; multary context: 1225 (214) ms; $t(30)=1.967$, $p=.059$) and negative sentences (binary context: 1305 (240) ms; multary context: 1271 (227) ms; $t(30) = 2.052$, $p = .049$), we did not find any interaction ($F < 1$). These main effects of polarity and verbal context provide evidence of participants' involvement in the comprehension of the spoken materials.

Eye movement data

First, we will describe the procedure for analyzing the eye-movement data generated by the EyeLink system. Bitmap templates were created for identifying each of the regions of interest (color circles) in each display. The output of the eye-tracker included the x and y-coordinates of participant fixations, which were converted into region codes using templates. The time period analyzed was from 500 ms before the onset of the critical word (the color word mentioned in the affirmative or negative assertion) to 1900 ms after the word. This time window was chosen to guarantee that there would be enough time for participants to comprehend negations (e.g., Kaup et al., 2006; Lüdtke et al., 2008). This period was divided into 20-ms time slots. For each time slot, the number of fixations on each color was counted and converted into fixation probabilities obtained from the four figures and the background (Fig. 2).

Fixation probabilities were obtained for display quadrants containing either (1) a figure of the color that was mentioned in the target sentences ("Mentioned Color"; e.g., a red figure for sentences like *the figure was (not) red*), (2) a figure of one of the colors mentioned in the verbal context sentence but not in the target sentence ("Alternative Color"; e.g., a green figure for a verbal context sentence like *the figure could be red or green* or *the figure*

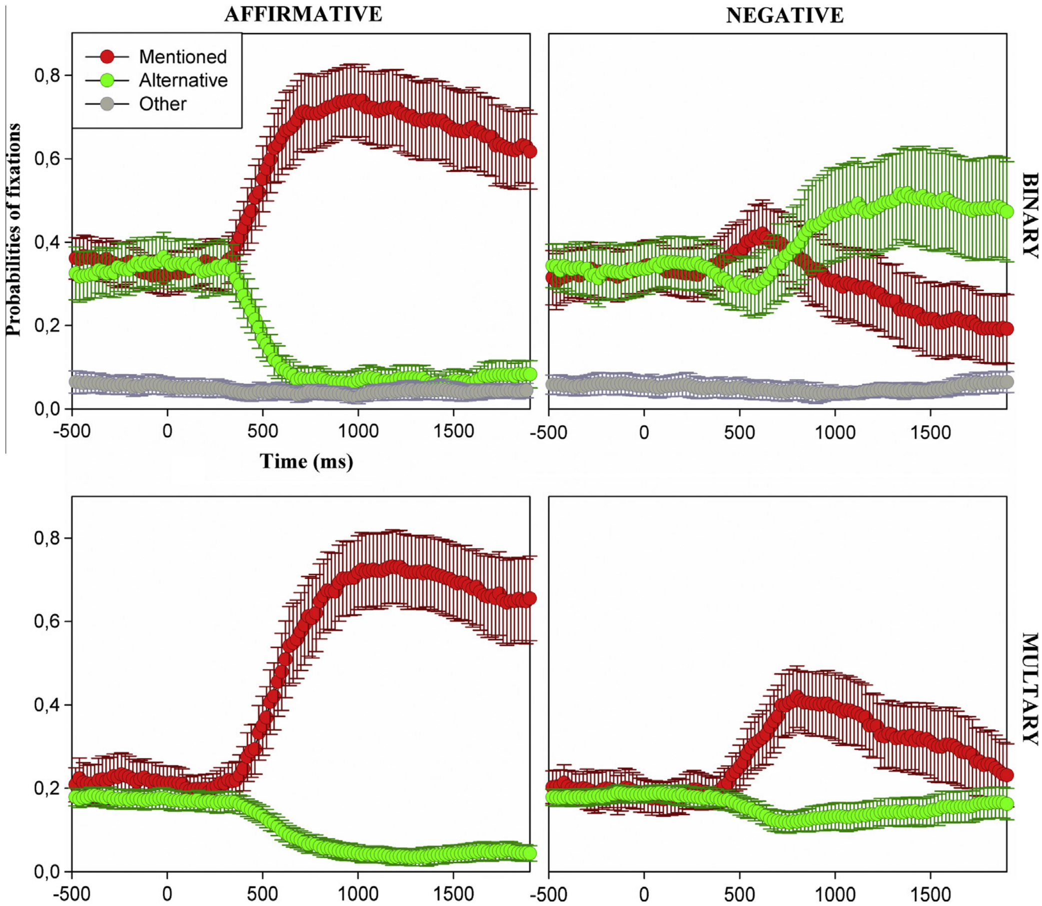

Fig. 2. Temporal course of affirmative (left) and negative sentences (right) for Binary context (top) and Multary context (bottom). The onset of the critical word (the color word mentioned in the affirmative and negative sentence) is represented by 0 on the horizontal axis. Error bars represent 95% confidence intervals by subject, such that no overlap between conditions indicates a significant difference. A pre-inspection of fixation probabilities on the *Other colors* for binary and *Alternative color* for multary context indicated no differences over time (*ps* > .2), so the average of these is shown as a single line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

could be red, or green, or blue, or yellow, followed by target sentences like *the figure was (not) red*), or (3) a figure of a color different from any of those mentioned in the verbal context and target sentences ("Other Colors"; e.g., a blue figure for verbal context sentences like *the figure could be either red or green* followed by a target sentence like *the figure is (not) red*). Fig. 2 shows the raw fixation probabilities. As can be seen, while the participants looked at the Alternative Color in binary context, they focused on the Mentioned Color in multary context for negative sentences.

T-test against baseline

Next, we calculated the ratio of proportion of fixation on each color over the sum of proportion of fixations on the four colors. This allows us to get the proportion of fixation on an object with respect to the others without background. Also, to avoid problems inherent to proportional data, participant and item averages were arcsin-transformed prior to *t*-test comparisons. Given that 180–200 ms are needed to account for an eye programming latency (Martin, Shao, & Boff, 1993), the mean of the first time region (0–100 ms) was considered to be the *baseline* and was used to conduct statistical comparisons against each time point until 1900 ms. The analysis was based on the methods described in Huettig and Altmann (2010). A False Discovery Rate (FDR) thresholding procedure was used to effectively control for the type 1 error due to multiple comparisons (90 for each condition; Genovese, Lazar, & Nichols, 2002).

Fig. 2 shows the impact of the spoken sentences on the time course of fixation for the Mentioned, Alternative and Other Color figures. In this figure, the graphs for affirmatives (left) show that there was an increase in fixation on the Mentioned Color accompanied by a decrease in fixation on the Alternative Color in both verbal contexts. In the binary context, the increase on the Mentioned Color started at 380 ms (pFDRcorr1 < .009 (subject analysis); pFDRcorr2 < .032 (item analysis)) and the decrease on the Alternative at 400 ms (pFDRcorr1 < .005; pFDRcorr2 < .008)). In the multary context, the significant differences with respect to the baseline started later, at 500 ms, for the Mentioned Color (pFDRcorr1 < .035; pFDRcorr2 < .036) and Alternatives (pFDRcorr1 < .035; pFDRcorr2 < .036)).

In contrast, the graphs for negatives (right) illustrate patterns of fixation that differ as a function of verbal context. For the binary context, there was an increase in fixation on the Alternative starting at 1340 ms (pFDRcorr1 = .012; pFDRcorr2 = .019). This latter pattern is preceded by a short period of increased fixations on Mentioned Color figures, which quickly fades into the stabilization of both the increase in fixations on the Alternative Color figure and the decrease in fixations on the Mentioned Color figure, which was only significant by item-analysis starting at 1220 ms (pFDRcorr2 = .023). For the multary context, there was an increase in fixation on the Mentioned Color (pFDRcorr1 = .026; pFDRcorr2 = .026) and a decrease in fixations on the Alternative Color (pFDRcorr1 = .026; pFDRcorr2 = .026) between 440 and 1600 ms.

The growth-curve analysis

T-test comparisons against the baseline reflected increase, decrease or no change in fixation ratios for the entities depicting the Mentioned and Alternative Colors. However, this was estimated for each condition separately, thereby precluding any direct comparison between either affirmative and negative sentences or binary and multary contexts. To analyze the differences between these conditions on the fixations toward the Mentioned Color, we used the growth-curve analysis (GCA) with orthogonal power polynomials, which properly takes into account the variations in trajectories over time (see Mirman, Dixon, & Magnuson, 2008). First, we modeled the effect of polarity separately for each verbal context. In this way, we could examine if the differences between affirmative and negative sentences lay at the intercept (which would reflect differences at overall fixation ratios), at the linear term (which would reflect differences at a monotonic change in fixation ratios), and at the quadratic term (which would reflect differences at the symmetric rise and fall rate of fixation ratios around a central inflection point). Second, to test directly whether the differences between affirmative and negative sentences varied across verbal contexts, we compared the polarity effect in the binary context (affirmative fixation ratios minus negative fixation ratios) against the polarity effect in the multary context. For each of the three comparisons, we report the deviance statistics, often called −2LL (minus 2 times the log-likelihood), the changes in deviance (AD), and the p-value. The change in deviance allows us to test whether including the parameter increases the fit of the model (see Table 1).

The results of Table 1 show that affirmative and negative sentences differed significantly in both verbal contexts. For both (Binary and Multary), there were significant effects at the intercept, which indicates that the overall fixation ratio on the mentioned color was higher for affirmative sentences than for negative sentences. There were also differences at the linear model, reflecting a different increase in fixation ratios for affirmative and negative sentences in both verbal contexts, and at the quadratic model, reflecting differences at rise and fall rate in fixation proportions. -2LL and AD values in Table 1 suggest that the differences between affirmative and negative sentences were in general larger for the binary contexts than for the multary contexts (see also Fig. 3). The comparison of the polarity effects (affirmative minus negative) across verbal contexts confirmed this point. It revealed differences at the intercept and at the quadratic term, but not at the linear term. That is, affirmative vs. negative differences showed a similarly timed monotonic increase for both verbal contexts, but were of a larger overall size and more pronounced rise/fall rate in the binary context.

Table 1
GCA results of the comparisons between affirmative and negative conditions within each verbal context (Binary and Multary) and of the comparison of the polarity effect (affirmative minus negative) across verbal contexts (Binary vs Multary).

Model	−2LL	AD	*p*<
Binary context			
Base	63,304.73		
Intercept	63,281.40	23.33	<.001
Linear	63,228.46	52.94	<.001
Quadratic	62,466.78	761.68	<.001
Multary context			
Base	63,661		
Intercept	63,645.59	15.41	<.001
Linear	63,608.25	37.34	<.001
Quadratic	63,430.11	178,14	<.001
Binary vs. Multary context			
Base	65,418.55		
Intercept	65,397.1	21.45	<.001
Linear	65,396.73	0.37	.546
Quadratic	65,285.37	111.36	<.001

Taken together, the two statistical approaches used to analyze the impact on fixations of sentence polarity and verbal context indicate that the differences between affirmatives and negatives were modulated by the type of verbal context, and also that this modulation was likely caused by negative sentences being processed differently in the binary context. Specifically, fixations on mentioned

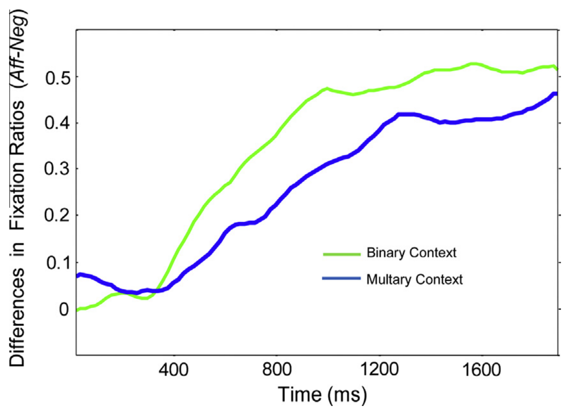

Fig. 3. Difference of probabilities of fixations between affirmative and negative sentences in binary context (green) and multary context (blue). The onset of the critical word (the color word mentioned in the affirmative and negative sentence) is represented by 0 on the horizontal axis. The differences between both types of sentence were higher for the binary context than for the multary context. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

colors increased immediately after critical word onset for negatives in the multary context, while such an increase was not observed for negatives in the binary context. In this latter context, it was the alternative color that varied with respect to the baseline, though the onset of the significant increase occurred beyond 1 s after critical word onset. By contrast, affirmative sentences showed similar increase of fixations on the mentioned color regardless of the verbal context.

General discussion

The present visual world eye-tracking experiment aimed to test the hypothesis that there are at least two ways to understand negation, depending on whether or not the verbal context makes the alternative available. Availability was manipulated here by giving participants two types of verbal contexts, which were presented while they were exploring a display depicting four differently colored figures. In the multary context, the verbal context named all four colors in the display (e.g., *the figure could be red, or green, or blue, or yellow*); in the binary context, only two colors were named (e.g., the *figure could be red or green*). Affirmative and negative sentences were presented right after this verbal context (e.g., *the figure was (not) red*). The predictions based on the two ways of processing negation were (1) that there would be an interaction between verbal context and sentence polarity reflected in fixations on the mentioned color (e.g., red), and (2) that this interaction would be due to negation promoting an increase in fixations on the mentioned color in the multary context and an increase in fixations on the alternative color in the binary context. Overall, these predictions were confirmed.

Growth-curve analysis revealed an interaction between sentence polarity and verbal context (see Fig. 3 and Table 1). Fixation ratios on mentioned colors were always larger in overall quantity for affirmative sentences than for negatives sentences. Yet, they differed as a function of verbal context. If one looks at the intercept term in the GCA model, the differences between the two verbal contexts would indicate that the fixation on the mentioned color was higher in the binary context than in the multary context. Also, the quadratic term of the model reveals that the polarity effect varied across verbal contexts, showing a more pronounced rise/fall rate of fixation ratios for the differences in the binary context. Visual inspection of fixation curves (see Fig. 2) suggests that this modulation by verbal context is due to negation.

The meaning of the above interaction and its relation to the two ways of processing negation can be clarified by the analyses against baseline run for each fixation ratio curve. These analyses revealed a similar pattern of increased fixations on the mentioned color for affirmatives in both binary and multary contexts. However, these individual curve analyses confirmed that negation, in contrast to affirmation, promotes different patterns of fixation across verbal contexts. For multary contexts, the pattern of fixation resembles in part that observed for affirmatives: an increase for the figure showing the mentioned color (negated in this case), as well as a decrease in fixation for the figures showing the three alternative colors. In contrast, the pattern for the binary context did not show any increase of fixations on the mentioned (negated) color, but rather an increase of fixations on the alternative. As we shall argue, the different pattern of fixations induced by negation as a function of verbal context confirms that there are two ways of processing negation, depending on the availability of the alternative.

This hypothesis is also confirmed through the temporal course of negation. The increase in fixation on the mentioned color started at 440 ms in the multary context, while the increase in fixation on the alternative color started at 1340 ms in the binary context. This difference could indicate that it is time-consuming to make the inference from ‘the figure is not red’ – the statement that subjects heard – to ‘the figure is green’. Also, people may keep two models (or possibilities) in mind, and this could slow down the processing of negation. In line with this, we found participants took longer to answer the written questions in the binary context. This suggests that the change toward the actual situation happens only in binary context. Indeed, if it has happened in multary context, the participants should have taken more time to answer because in that condition there are more alternatives to attend, and that was not the case. The tendency to shift fixations to the available alternative might be accounted for by a preference to exchange the negated model for an affirmative model, because it may be easier to store an affirmative model. Negation can be stored as a ‘mental footnote’ and people soon lose track of these footnotes because they are hard to remember (Johnson-Laird, 2001).

However, there are cases, such as the multary context, in which the alternative is not available and therefore many alternatives are possible to describe what the alternative (or actual situation) is. Results showed that participants focused on the figure corresponding to the mentioned color (or negated situation) in the multary context. This finding is consistent with the possibility that negation is represented symbolically, likely as a mental tag (Beltrán, Orenes, & Santamaría, 2008; Clark & Chase, 1972; Giora, 2006; Giora, Fein, Aschkenazi, & Alkabets-Zlozover, 2007; Khemlani et al., 2012; Mayo, Schul, & Burnstein, 2004; Schul, 2011). This would arise as a consequence of the limitations of working memory: multiple models can overload its processing capacity and lead to errors. Johnson-Laird (2001) pointed out that the fewer the number of models needed for an inference, the easier the inference should be by the effect of limited memory. In short, it is likely that individuals will exchange one negated model for one affirmative model (alternative), because negation is hard to remember. However, people would prefer to maintain negation rather than two or more possible affirmative models.

Our results pose problems to the two-step processing defended in Kaup et al. (2006). It seems that negation could be understood by simulating the alternative directly, like Anderson et al. (2010) and Tian et al. (2010) have proposed. However, our results also showed that representing the actual situation is not necessary to understand negation. In other words, negation can maintain its own meaning in symbolic format. Alternatively and according to the two-step theory, the differences between binary and multary contexts might suggest that while comprehenders look at the actual situation in the binary context, they cannot find a picture that matches the mental representation of a negative. Given that, the question that still arises is what do people represent when there is no a clear actual situation? Our data show that the change of visual attention from the negated situation toward the actual situation is time-consuming, and we only found an increase of visual attention in the mentioned word around 440 ms. As a result, it seems that there was no shift of attention in the multary context. Also, if the two steps happened, it will be more difficult to represent an unspecified representation (i.e., an unspecified color figure) or at least similar (i.e., an empty figure) in the multary context than a specific representation (i.e., a green figure) in the binary context. On the contrary, our behavioral data showed that the time to answer the written questions take longer in binary context than multary context. Therefore, those results suggest that while one representation is maintained in the multary context (the negated situation), two representations are activated in binary context (the negated situation and the alternative). As Barsalou (2008) pointed out, the iconic simulation system is closely integrated with the linguistic system. Our results fit well with model theory, which accepts the possibility that negation can be represented iconically through its alternative, but there still exists the possibility of using a mental tag to represent the negated argument.

One criticism of our study would be that the lower degree of attention on the mentioned color for negative sentences as compared to affirmative ones, particularly in the multary context, might indicate a shift of attention on the part of the comprehender from the negated argument to the alternatives. However, the data did not show an increase of fixations on the alternative, just an increase of fixations on the mentioned color. For the two-step theory, one might also be tempted to argue that this difference in fixations between affirmative and negative sentences could be reflecting the representation of an unspecified or empty situation. However, if this were the case, we would expect to find a pattern in fixations similar to that found in the binary context, where participants looked at the negated argument and the alternatives from the beginning. In the multary context, however, participants just significantly increased fixations on the negated argument, and so the data cannot prove that the alternatives were receiving attention in the multary context.

In our view, the lower degree of attention on the mentioned word for negative sentences is related to the degree of correspondence between the meaning of the sentence and the image. For instance, while there is a direct correspondence between the meaning of the affirmative sentence (e.g., *the figure is red*) and the image (a red figure), this is not the case for the negative sentence, as there is no image in the world that could capture the meaning of negation. Although people looked at the red figure in the multary context as a consequence of representing 'not red' instead of 'green, or yellow, or blue', the correspondence is not direct. The red figure is false with respect to the meaning of the sentence. This hypothesis supports the idea that negation could be represented explicitly. This latter representation offers a major advantage for the cognitive system, because it prevents the memory from becoming overloaded with multiple possibilities and their complexity (see Johnson-Laird, 2001). In sum, we can conclude that the representation of the alternative is not necessary for understanding negation, but just one possibility. From a different line of research, other authors have also come to suggest that the rejection of the negated argument to represent the actual one is not a mandatory operation for negative sentence understanding (Giora, 2006).

The lower degree of visual attention on the mentioned color for the negative sentences could be related to the longer time needed to answer the written questions in the present experiment. Literature on negation has shown that people take longer and make more mistakes after negative sentences than after affirmatives (see Carpenter & Just, 1975; Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Clark & Chase, 1972; Trabasso et al., 1971; Wason & Johnson-Laird, 1972; Wason & Jones, 1963). In addition, this lower visual attention on the mentioned color for negative sentences could be related to the lesser recall of negated concepts as compared to affirmative ones. Embodiment theory claims that negative concepts are less accessible (through recall) than affirmative concepts, because the negated situation is replaced by the actual situation (Kaup, 2001). On the other hand, propositional theory holds that negation is an explicitly represented operator that takes a whole proposition in its scope. As the negation operator encapsulates the negated concept, it is less accessible (Fillenbaum, 1966; Hasson & Glucksberg, 2006; Lea & Mulligan, 2002; MacDonald & Just, 1989). This latter point of view fits better with our results, because the negated situations (or the mentioned color) received less attention than the affirmatives in both the binary and multary contexts from the beginning, while an inhibition of the negated situation due to the change toward the alternative only happened in the binary context. In sum, the lower amount of visual attention paid to the mentioned color for negative sentences, as revealed by the persistent differences with affirmatives, could be related to the fact that the negative concepts are harder to process and recall.

It is important to note that the mentioned color (the red figure) is false with respect to the negative sentence (e.g., *the figure is not red*). This may be the first study, to our knowledge, that shows how humans focus on what is false. All studies of eye-movements have shown that people focus on the object that corresponds to the referent, or if the referent is not present, on a related semantic object (Duñabeitia, Avilés, Afonso, Scheepers, & Carreiras, 2009; Huettig & Altmann, 2010). However, our participants focused on what is false in order to understand negation. In our view, this peculiarity is related to the particular function of negation in communication. It is used to deny a false argument (or misconception), thus focusing on what is false and rejecting it. For example, if someone thinks that 'bats are birds', then the hearer could use negation to reject the argument 'bats are *not* bats'. The focus of attention is what bats are *not*, irrespective of whether one knows what they are. This function of negation could be particular or unusual, but it is essential in language comprehension, since it is present in all natural and artificial languages and from an early age.

Our interpretation of the results involves assumptions about how visual and verbal contents interact, and more specifically, about how eye fixations are driven by visual attention and sentence processing, as well as by the interaction between them. Nowadays, it is accepted that visual, phonological and semantic information is integrated during speech processing in a visual world paradigm, which might be taken as partially supporting the eye-mind hypothesis already anticipated by Just and Carpenter (1976). Yet, the mechanisms involved in the multimodal integration remain underspecified (Smith, Monaghan, & Huettig, 2013) and some limitations of the visual world paradigm (Pickering, McElree, & Garrod, 2004) and covert attention (Posner, 1980) have been widely discussed. For our study, we assumed integration between visual information and sentence meaning to take place likely in working memory, through a co-activation of the representations subtending visual and conceptual processing. Our results showed that people looked at the red figure after hearing 'the figure is red' and they looked the green figure after hearing 'the figure is not red' in the binary context. That is to say, the direction of their gaze is consistent with the meaning of processing; this consistency must then also exist in the multary context. In support of this assumption, parallel evidence exists showing availability in working memory for both mental representations involved in sentence comprehension and attended visual information (Awh & Jonides, 2001; Johnson-Laird, 1983; Kaup et al., 2006). Importantly, there is another assumption in our study: given that only verbal information changed through the trials, we expected an asymmetrical integration between visual and conceptual information. In particular, we predicted that, as a result of the integration occurring in working memory, visual attention would be modulated in the direction of the conceptual unfolding of the speech. In other words, sentence processing was anticipated to act as a selection mechanism for visual attention and, consequently, for eye fixations. As already described, our results seem to fit this picture nicely, even though it is quite possible that other factors were affecting to the way participants explored the visual environment. Further research should be conducted, however, to determine in more detail the mechanisms involved in the interaction between sentence meaning processing, visual attention and fixations in visual world paradigms like the one used in the present study.

Finally, it is important to consider whether the results of this study (which uses exclusively perceptual features, i.e. colors) could be generalized to include more abstract concepts. In our view, a shift of attention toward the alternative affirmative such as that tested in our study depends more on the availability of the alternative than on the format used to represent the concepts. As the reader can corroborate in any association corpus, such as the Spanish free-association norms (Fernández, Díez, Alonso, & Beato, 2004), the two words of binary predicates are highly associated in the case of both perceptual and abstract concepts; this association should facilitate the shift of attention to the alternative, which will be modulated by its accessibility regardless of the format used to represent the negated argument (e.g., *the figure is not red* or *the door is not open*). In sum, the representation of negation (the negated argument or the alternative) depends on the availability of the alternative, and when this is unavailable, the mental representation of the sentence calls for symbolic tags.

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