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BROCA'S AREA ACTIVITY IN THE LEXICAL SEMANTICS OF VISUAL CAUSAL EVENTS

ACTIVIDAD EN EL ÁREA DE BROCA ASOCIADA CON LA SEMÁNTICA LÉXICA DE LOS EVENTOS CAUSALES VISUALES

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ABSTRACT

From a cognitive linguistics perspective, is assessed the effects of causative constructions on the activity of Broca's area during the processing of visual causal and non-causal events. Lexical causatives (e.g., the orange ball moves the purple ball) describe only direct causal events whereas periphrastic causatives (e.g., the orange ball causes the purple ball to move) describe both direct and indirect causal events. Based on this difference, is used lexical and periphrastic causatives as verbal instructions that directed participants to judge billiards balls collisions depicting direct, indirect, and non-causal events. By using functional magnetic resonance imaging (fMRI) and region of interest analysis, is found that judgments of all three visual events more strongly activated Broca's area following the periphrastic instruction than following the lexical instruction, and judgments of direct events produced stronger activity in Broca's area than indirect events. Interestingly, causal judgments were segregated between pars opercularis and pars triangularis. Results are discussed within the context of the linguistic category priming hypothesis, linear ballistic accumulator models, and the hierarchical organization of the prefrontal cortex. Because this our data suggest functional segregation during causal judgments, it is proposed that effective connectivity between these regions is worth evaluating in a follow-up study via dynamic causal modeling of fMRI data.

Keywords: Causal judgment; causal conceptualization; lexical causatives; periphrastic causatives; Broca's area.

RESUMEN

Desde una perspectiva de la lingüística cognitiva, se evalúa los efectos de las construcciones causativas en la actividad del área de Broca durante el procesamiento de eventos visuales causales y no causales. Las estructuras léxicas causativas (e.g., la bola anaranjada mueve a la bola púrpura) describen solamente eventos causales directos mientras que las estructuras perifrásticas causativas (e.g., la bola anaranjada hace mover a la bola púrpura) describen tanto los eventos directos como los indirectos. Basados en esta diferencia, se emplea estructuras causativas léxicas y perifrásticas como instrucciones verbales que dirigían a los participantes a juzgar si colisiones del tipo "bolas de billar" simulaban eventos causales directos, causales indirectos y no causales. Mediante el uso de resonancia magnética nuclear funcional (RMNf) y el análisis por región de interés se encontró que los juicios sobre los tres tipos de eventos activaron más la región de Broca cuando eran precedidos por la instrucción perifrástica que cuando eran precedidos por la instrucción léxica. Por otra parte, los juicios sobre los eventos directos producían mayor actividad en el área de Broca que los eventos indirectos. Se encontró interesante que los juicios causales estuvieron asociados a actividad segregada en el pars opercularis y en el pars triangularis. Los resultados son discutidos en el contexto de la hipótesis del "priming" lingüístico de categorías, los modelos lineales de acumulación balística y la organización jerárquica de la corteza prefrontal. Porque estos datos sugieren segregación funcional durante los juicios causales, se propone una futura investigación sobre la conectividad efectiva entre estas regiones empleando modelos causales dinámicos de RMNf.

Palabras clave: Juicios causales, conceptualización causal, estructuras léxicas causativas, estructuras perifrásticas causativas, Área de Broca.

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1. INTRODUCTION

Humans organize the structure of the world via causal conceptualization. Causal conceptualization helps to predict the spatiotemporal dynamics of the environment. For example, the representation of the causal structure of rear-end collisions allows us to both predict *when* the collision occurs and *update* actions accordingly. (Limongi, Pérez, Modroño & González-Mora, 2016; Limongi, Silva & Góngora-Costa, 2015; Limongi, Sutherland, Zhu, Young & Habib, 2013;

Young, Rogers & Beckmann, 2005; Young & Sutherland, 2009). The adaptive importance of causal conceptualization has given rise to a research agenda aiming to unveil its neural basis (Blakemore et al., 2001; Fonlupt, 2003; Fugelsang & Dunbar, 2005; Fugelsang, Roser, Corballis, Gazzaniga & Dunbar, 2005; Green, Kraemer, Fugelsang, Gray & Dunbar, 2010).

Depictions of billiards balls collisions have been the preferred stimuli used in the neuroscientific research of visual causality. In general, spatiotemporal contiguities of collisions are referred to as *direct* causal events whereas violations of either the spatial or the temporal contiguity are referred to as *non-causal* events. This differentiation relies on psychophysical studies about the relationship between visual causation and spatiotemporal contiguity (Choi & Scholl, 2004; Kerzel, Bekkering, Wohlschläger & Prinz, 2000; Scholl & Nakayama, 2002; Scholl & Tremoulet, 2000; Thines, Costall & Butterworth, 1990; Young et al., 2005).

In general, it appears that the brain processes visual causal events in two stages. Whereas spatiotemporal components of events would be processed in posterior brain areas (Blakemore et al., 2001; Fonlupt, 2003; Fugelsang et al., 2005; Straube & Chatterjee, 2010; Woods et al., 2014), causal judgments would incorporate inference and decision making, two cognitive processes commonly attributed to frontal structures (Fugelsang & Dunbar, 2009; Miller & Cohen, 2001; Roser, Fugelsang, Dunbar, Corballis & Gazzaniga, 2005; Woods et al., 2014). For example, Fugelsang et al. (2005) found that when participants are instructed to detect spatiotemporal contiguities in billiards balls collisions, activity in temporal and parietal cortices increase activity when compared with the detection of spatial and temporal violations respectively. Fugelsang et al. (2005) also found that when spatiotemporal contiguities were compared with conjoint spatial and temporal violations, activity in the right prefrontal cortex increased, suggesting that activity in the right prefrontal cortex is associated with causal integration as a whole. This suggestion is consistent with data of Roser et al. (2005) who had split-brain patients perform causal judgments of billiards balls collisions. Causal and non-causal events were randomly presented to either their left or right visual fields, and patients' perceptions of spatiotemporal contiguities were more accurate on right visual-field trials than on left visual-field trials.

In the neuroscientific literature, *direct causation* depicted in billiards balls collisions is frequently referred to as *perceptual causality*. In contrast, *causal inference* (i.e., higher-order causal judgment) has been studied using abstract stimuli such as lightboxes (Roser et al., 2005) and cartoons (Fugelsang & Dunbar, 2005). For example, Fugelsang and Dunbar (2009) relied upon the tenet that language plays a special role during higher-order causal reasoning and suggested that the left hemisphere should show an advantage over the right hemisphere during causal inference. A study with neurophysiological patients supports this claim. Using light switches and lightboxes, Roser et al. (2005) found that split-brain patients judged temporal switch-on/light-on and switch-off/light-off contiguities as causal relations only when stimuli were presented in the left visual field. They concluded that the left hemisphere outperforms the right hemisphere at judging such abstract causal events. Furthermore, Fugelsang and Dunbar (2005) had healthy subjects judge cartoons depicting complex causal and non-causal scene and found increased activity in Broca's area when participants judged abstract causal scenes compared with non-causal scenes.

Although Broca's area has been traditionally related to syntactic processing (Embick, Marantz, Miyashita, O'Neil & Sakai, 2000), increasing evidence provided by cognitive neuroscience studies suggests that semantic integration and conceptualization also recruit activity in this region (Hagoort, 2005; Hagoort, Hald, Bastiaansen & Petersson, 2004; Rogalsky & Hickok, 2011). Moreover, Broca's area is located in the ventral part of the prefrontal cortex which seems to be functionally organized in hierarchies of concrete-to-abstract conceptualizations (Christoff & Gabrieli, 2000; Green et al., 2010). These facts lead to infer that activity in Broca's area could be associated with language-driven causal conceptualization of concrete visual causal events (e.g., billiard balls collisions).

From the perspective of cognitive linguistics and lexical semantics (Geeraerts & Cuyckens, 2010; Talmy, 2000; Wolff, 2003; Wolff & Song, 2003), humans distinctively and accurately conceptualize different causal events via specific linguistic structures. For example, lexical and periphrastic causatives respectively mediate the conceptualization of simple and more complex causal events (Wolff, 2003; Wolff & Song, 2003). Lexical causatives are structures that involve one clause with a transitive verb such as in "Katrina destroyed New Orleans". They represent direct causation which occur, for example, when a car knocks down a tree. In this event, no intermediate object intervenes between the two actors (the car and the tree).

Conversely, biclausal, analytic, or periphrastic causatives (Kemmer & Verhagen, 1994) include one causal predicate with a causative verb such as cause, have, or make (Rappaport Hovav, Doron & Sichel, 2010; Wolff, 2003) and an effect predicate with either a transitive or an intransitive resultative verb (e.g., rise). For example, in the phrase "a supply shortage causes gas prices to rise" the matrix verb "cause" embeds the resultative verb "rise" (Kemmer & Verhagen, 1994). Psycholinguistic data show that participants describe not only direct but also indirect events with a periphrastic structure (Wolff, 2003). Unlike direct causation, indirect causation involves at least two actors which interact via a third object serving as a non-enabling intermediary. Indirect causation occurs, for example, when a car strikes a tree, the tree falls down, strikes a window, and the window breaks. In this event, the falling tree acts as a non-enabling intermediary.

The above antecedents lead us to infer that although Broca's area is involved in abstract causal judgment, different causal constructions could drive differential activity in this area during causal judgments of visual events. In the current work, it was used functional magnetic resonance imaging and region of interest (ROI) analysis to evaluate this hypothesis. Specifically, we used lexical and periphrastic constructions as verbal instructions in a visual causal judgment task and observed the hemodynamic activity in Broca's area during the processing of visual causal and non-causal events that followed the verbal instructions.

2. MATERIAL AND METHODS

2.1. Participants

Fourteen right-handed normal volunteers (18 - 36; 8 Males) participated in the study and received a $25 gift card for participation. Participants were students from Southern Illinois University Carbondale. They reported normal vision, no drugs history, no neurological history, and normal hearing. Two participants were excluded due to computer failure. Participants signed informed consent forms, and the study was approved by the Human Subjects Committee of Southern Illinois University Carbondale.

2.2. Materials

2.2.1. Visual causal events

Three different animations based upon the Michottean launching paradigm were created. The Michottean launching paradigm consists of the visual illusion of two balls colliding like billiard balls (Thines et al., 1990). The stimuli differed in their causal nature: direct causal (DC), indirect causal (IC), and indirect non-causal (INC) events. Each animation consisted of two balls, an orange ball to the left of a computer screen and a purple ball in the middle of the screen. In the IC and INC animations, a blue cylinder lay equidistant between the horizontal path created by the orange and purple balls.

At the beginning of each animation sequence, the orange ball began to move to the right. In the DC animation, the orange ball "struck" the purple ball, at which point the orange ball stopped moving and the purple ball started moving to the right. In the IC animation, the orange ball struck the blue cylinder and stopped moving. The blue cylinder then moved towards the stationary purple ball, struck the purple ball, and stopped at which point the purple ball began moving to the right. In the INC animation, the orange ball and the blue cylinder were located below the horizontal position of the purple ball. As in the IC animation, the orange ball struck the blue cylinder at which point it stopped and the blue cylinder began moving to the right. When the right edge of the blue cylinder reached the same vertical position as the left edge of the purple ball (even though they were not on the same horizontal dimension), the blue cylinder stopped and the purple ball began moving to the right. See Figure 1 for a graphical depiction of each condition.

2.2.2. Linguistic constructions

Natural language comprises a large number of causal verbs that potentially mediate the conceptualization of an equally large number of causal events via lexical and periphrastic constructions. In this work, however, we only used the verbs *move* and *cause to move*. As stated in this hypothesis, differences in the processing of lexical and periphrastic constructions involving these verbs should elicit differential activity in Broca's area during judgments of direct and indirect causal events. To this aim, the periphrastic causative construction "judge whether the orange ball causes the purple ball to move" and the lexical causative construction "judge whether the orange ball moves the purple ball" were used as verbal instructions.

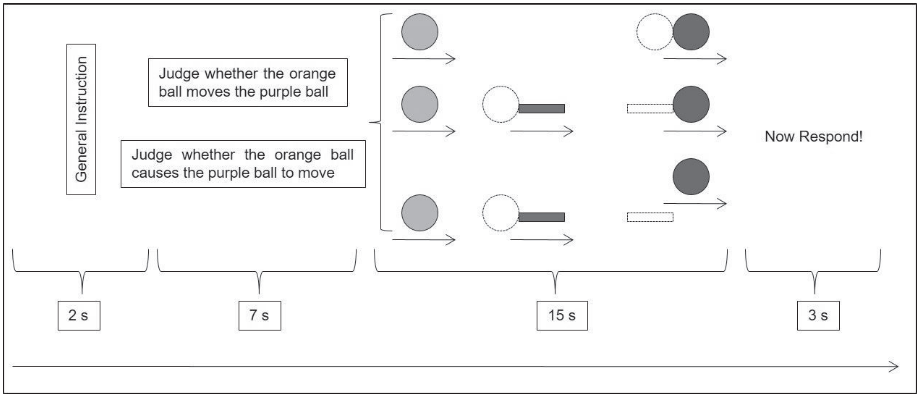

Figure 1. Linguistic stimuli, visual event stimuli, and task design. In a single block, participants read a general instruction followed by one of the two verbal instructions and observed one of the three visual events six consecutive times before responding. Visual events: direct causal (top), indirect causal (center), indirect non-causal (bottom).

3. EXPERIMENTAL DESIGN AND STIMULI PRESENTATION

Participants performed a two forced-choice decision making task (2FCT). The task was defined within a repeated measures designed that comprised 2 (Verbal Instruction: Periphrastic vs. Lexical) × 3 (Animation: IC, INC, DC) conditions. A total of 12 three-minute fMRI runs were performed. During each run, the order of Verbal Instructions was randomized. Following each verbal instruction, subjects were shown the three causal animations (IC, INC, DC) in a randomized order. Thus, participants observed all animations under one verbal instruction before observing all animations under the second verbal instruction. Each run consisted of 6 blocks. Each individual block lasted 27 seconds (Figure 1) and consisted of two phases (verbal instruction and visual event) with the following sequence: (a) general instructions (2 sec), (b) periphrastic or lexical instruction (7 sec), (c) one of three animation sequences (2 sec) repeated 6 times with a 500 ms blank period between each repetition (15 sec), and (d) a response window prompting to respond ("Now Respond", 3 sec). During the response window, participants were required to respond "yes" or "no" (to indicate whether the animation was reflective of the periphrastic or lexical instruction) by pressing respectively the right index or middle buttons of a response pad. We previously tested this sequence of events in a within-laboratory pilot study.

Animations were presented on the center of an MRI compatible LCD screen (IFIS-SA, InVivo, Orlando, FL). The LCD screen was attached to the back of a standard MRI head coil. Participants viewed the LCD screen via a mirror placed directly above their eyes. Responses were recorded by MRI compatible response buttons.

3.1. Scanning and Analysis

The fMRI scanning was performed on a Philips Intera 1.5 T magnet using a standard head coil. Each functional run (12 in total) consisted of 72 contiguous whole-brain volumes (T2* single-shot echo-planar imaging EPI, TR = 2500 ms, TE = 50 ms; flip angle, 90°, FOV= 220 × 220 mm^2, 64 × 64 matrix, 3.44 × 3.44 × 5.5 mm voxels, 26 × 5.5-mm horizontal slices, 0 mm gap, ascending interleaved acquisition, 8 prescan images were also collected and discarded). Conventional high resolution T1 weighted 3D structural images were acquired at the end of the functional imaging stage.

Imaging data were analyzed with SPM8 (Flandin et al., 2008) implemented in Matlab (MathWorks, 2008). Functional EPI volumes were slice-time corrected for ascending interleaved acquisition order, realigned and motion corrected to the mean image of the session with a 7th degree B-spline interpolation method, and resliced with a 4th degree B-spline interpolation method. After realignment, images' global signal means per functional run were evaluated for outliers or scanning artifacts. Three percent of the volumes of one subject were repaired by means of linear interpolation from the adjacent images. Image quality assessment and repair was performed with ArtRepair (Mazaika, Whitfield & Reiss, 2007). Images were further coregistered to the subjects' structural images (subjects' structural images were segmented using the SPM default tissue probability maps and normalized), normalized to the subjects' normalization parameters, spatially smoothed with an 8-mm Gaussian filter and resliced to 2 x 2 x 2 mm voxels. A 128 s high-pass filter was applied to each time course in order to eliminate low frequency noise.

FMRI data from all participants (14) were analyzed. We fit a general linear model to participants' individual data with the six conditions: lexical direct causal (L-DC), lexical indirect causal (L-IC), lexical indirect non-causal (L-INC), periphrastic direct causal (P-DC), periphrastic indirect causal (P-IC), and periphrastic indirect non-causal (P-INC) as effects terms convolved with a canonical hemodynamic response function. Response times collected during the response window were included as a parametric regressor. Six head-motion parameters from the realignment were used as covariates of no interest. Every run was modeled as a series of the 12-sec epochs comprising the 6 animations (Henson, 2007). Participants' summary statistics per condition were imported into a 2 (verbal instruction) by 3 (visual event) repeated measures analysis of variance as a random effects analysis.

Broca's area was defined as a region of interest by means of the automatic anatomic labeling atlas on the Wake Forest University Pickatlas tool (Maldjian, Laurienti, Kraft & Burdette, 2003). A single mask comprising the left pars triangularis and left pars opercularis (Hagoort, 2005) was constructed with 0 dilation; the frontal operculum was not included. Voxel-wise maps were limited to the pre-specified region of interest ($p < .001_{uncorrected}$) and small volume corrections ($FWE < .05$) were applied onto a five-millimeter sphere centered at the peak activation. Only peaks of activity surviving correction at a cluster level are discussed in this manuscript. Mean contrast values as estimates and 95% confidence interval were calculated on data extracted from each peak activity within clusters. However, for the interested reader pursuing meta-analytic analysis (Eickhoff, Bzdok, Laird, Kurth & Fox, 2012) peak whole-brain activations thresholded at an uncorrected $p < .001$ are also reported.

Behavioral response times were collected from all participants (14) during the response window. We report a repeated measures analysis of variance or the log-transformed response times (to ensure normality) of all participants. However, causal judgments (i.e. yes / no) from only five participants were recorded due to software error (60 trials). To overcome this limitation and to ensure the correct interpretation of our data, causal-judgment data of these five subjects were analyzed via non-parametric tests. Specifically, we performed the Cochran's Q-test for the omnibus analysis and the McNemar Chi square test for planned contrasts on the behavioral responses. Responses were coded as "1" for positive responses and "0" for negative responses.

4. RESULTS

4.1. Behavior

4.1.1. Causal judgments

Figure 2 shows frequencies of causal judgments to the causal (DC and IC) and non-causal (INC) animations during the scanning sessions. Cochran's Q-test revealed overall statistical significant difference among conditions, $Q(5) = 17.59$, $p = 0.003$. As predicted, following the periphrastic instruction the frequency of "yes" responses was higher for the IC events than for the INC events, $\chi^2(1) = 52.01$, $p < 0.001$. Also as expected, following the lexical instruction the frequency of "yes" responses were higher for the DC than for the IC, $\chi^2(1) = 19.36$, $p < 0.001$. Of most importance, the frequency of "yes" responses during the judgments of IC was higher following the periphrastic instruction than following the lexical instruction, $\chi^2(1) = 21.04$, $p < 0.001$.

4.1.2. Response times

The repeated measures analysis of variance yielded main effect of verbal instruction $F(1, 825) = 4.82$, $p = 0.03$ (Figure 3). The mean log-transformed response time during the periphrastic condition was shorter (M = 2.70 ms, SE = 0.06) than during the lexical condition (M = 2.73 ms, SE = 0.06). Neither main effect of Animation $F(2, 825) = 0.51$, $p = 0.60$ nor Verbal Instruction × Animation interaction $F(2, 825) = 0.19$, $p = 0.83$ was detected.

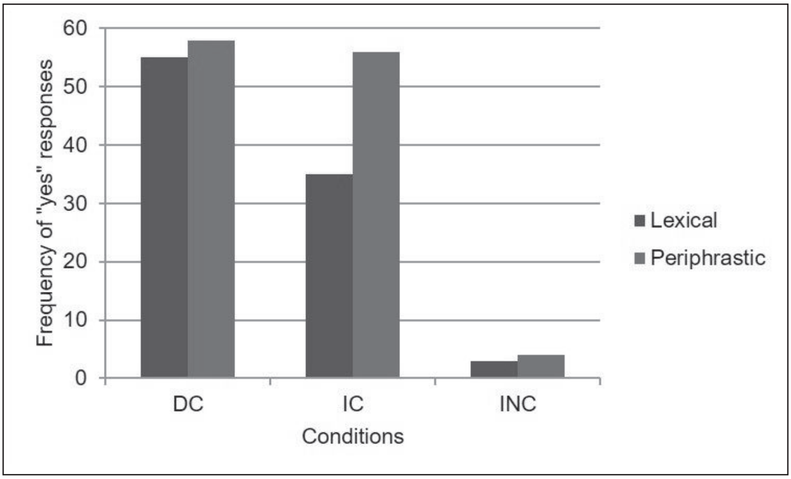

Figure 2. Frequencies of positive (yes) causal judgments of five subjects.

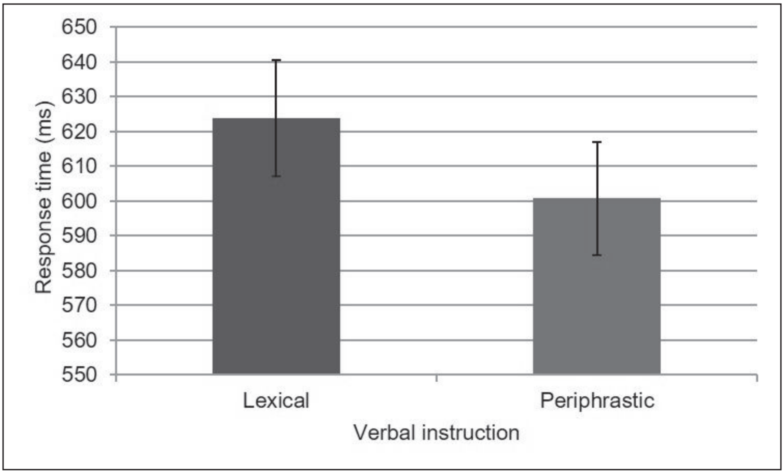

Figure 3. Means (+/- SE) of raw response times recorded during the response window collapsed across visual animations. Note that statistical analysis was performed on log-transformed values.

4.2. fMRI

The omnibus test yielded significant main effect of verbal instruction, $F(1, 66) = 12.19$; (k = 9, peak x y z = -54 23 7, Z = 3.13, $p = .012_{SVC}$). The BOLD response was stronger following the periphrastic than the lexical instruction across all animations in the pars triangularis (k = 13, peak x y z = -54 23 7, Z = 3.33, $p = .006_{SVC}$). The Verbal Instruction x Animation interaction was also significant in the pars triangularis, $F(2, 66) = 13.52$; (k = 13, peak x y z = -33 38 7, Z = 4.22, $p < .001_{SVC}$).

Judgments of the three visual events yielded stronger activity in Broca's area following the periphrastic verbal instruction than following the lexical instruction (Figure 4). First, the pars triangularis was more active during judgments of direct events (k = 17, peak x y z = -48 23 19, Z = 4.66, $p = .002_{SVC}$). Second, judgments of IC events yielded stronger activity in the pars opercularis (k = 3, peak x y z = -60 5 13, Z = 3.34, $p = .003_{SVC}$). And, third, when participants judged INC events, the pars triangularis showed stronger activity in two separate clusters (k = 9, peak x y z = -54 23 10, Z = 3.39, $p = .005_{SVC}$; and k = 10, peak x y z = -33 38 10, Z = 4.22, $p < .001_{SVC}$).

Finally, we investigated whether the periphrastic instruction yielded differential activity across visual events. Judgments of direct events elicited stronger activity than judgments of indirect events in the pars triangularis (peak x y z = -48 23 19, Z = 3.40, $p = .005_{SVC}$). No difference was found in the P-DC vs. P-INC contrast or in the P-IC vs. P-INC contrasts. Table I shows the activity in areas after performing a whole-brain exploratory analysis

Because participants made positive and negative causal judgments of direct and indirect events across verbal constructions, the analysis reported above does not inform us whether the fMRI data arose from collapsed positive and negative responses or whether such responses gave rise to different activations. In other words, did the sign (positive or negative) of the behavioral response affect the neural activation in our region of interest?

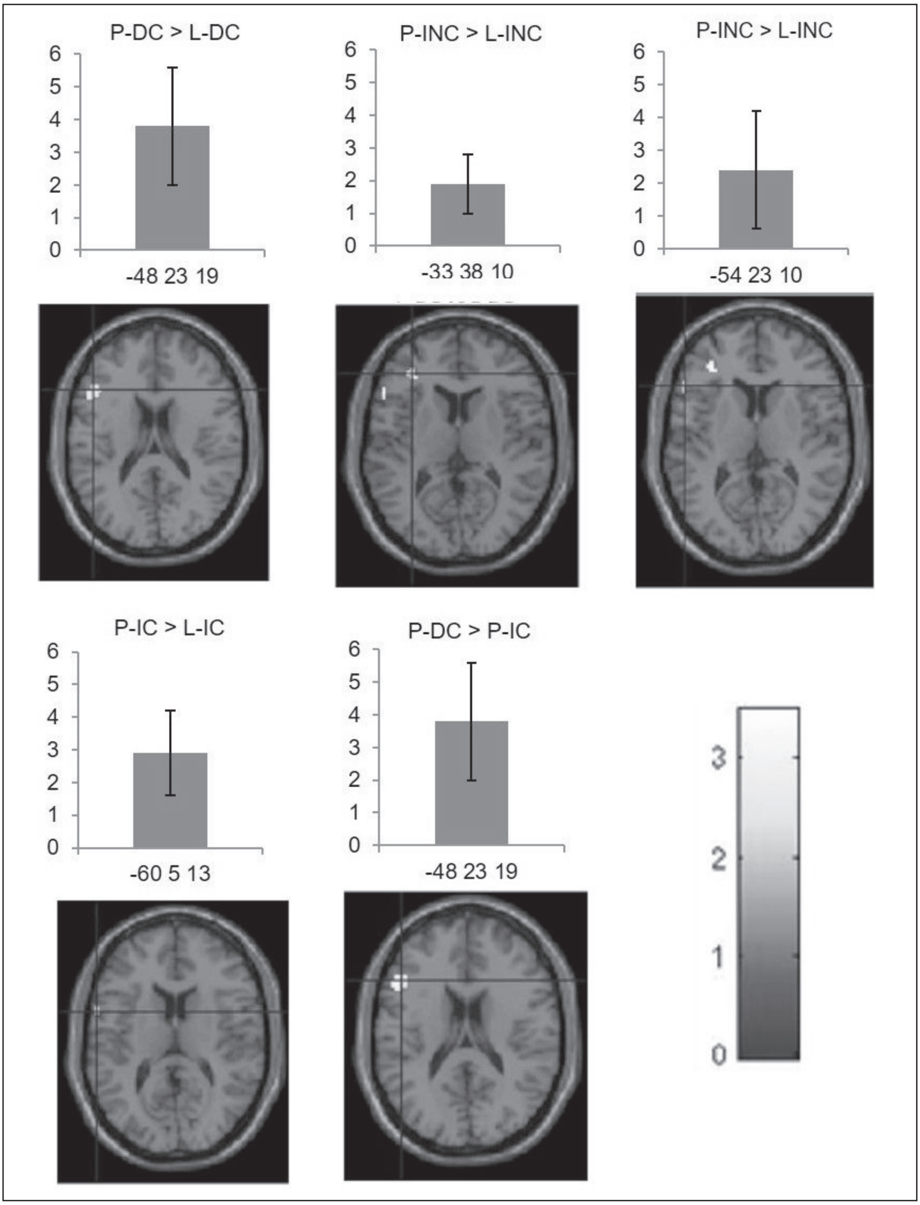

Figure 4. Loci of activity in Broca's area overlaid on the SPM anatomical template. Error bars represent 95 % confidence interval of the contrast value. PI (Periphrastic causative Indirect Causal), P-INC (periphrastic causative – indirect non-causal), P-DC (periphrastic causative – direct causal), L-INC (lexical causative – indirect non-causal), L-IC (lexical causative – indirect causal), L-DC (lexical causative - direct causal).

Table I. Whole brain activation activity during the visual animation phase of the task.

Contrast	Region	Cluster Size	Z	Peak p(unc)	MNI Coordinates		
					x	y	z
P-DC > L-DC	Broca's area (Pars Triangularis)	17	4.66	<.001	-48	23	19
	Thalamus(Pulvinar)	8	3.592	<.001	30	-24	6
	Superior Temporal Gyrus	11	3.299	<.001	48	-21	6
P-IC > L-IC	Cingulate Gyrus	8	3.975	<.001	-24	-6	36
	Thalamus(Pulvinar)	27	3.775	<.001	30	-27	6
P-INC > L-INC	Superior Temporal Gyrus	18	3.334	<.001	45	-27	6
	Middle Temporal Gyrus		3.562	<.001	-27	-54	27
	Transverse Temporal Gyrus	26	3.509	<.001	-42	-33	12
	Medial Frontal Gyrus	9	3.403	<.001	-9	27	45
	Broca's area (Pars Triangularis)	9	3.39	<.001	-54	23	10
	Broca's area (Pars Triangularis)	10	4.22	<.001	-33	38	10
P-DC > P-IC	Broca's area (Pars Triangularis)	5	3.4	<.001	-48	23	19

Note. PI (Periphrastic causative Indirect Causal), P-INC (periphrastic causative – indirect non-causal), P-DC (periphrastic causative – direct causal), L-INC (lexical causative – indirect non-causal), L-IC (lexical causative – indirect causal), L-DC (lexical causative - direct causal).

To answer the above question, we performed a Bayesian model estimation and comparison with participants as random effects (Rosa, Bestmann, Harrison & Penny, 2010; Stephan, Penny, Daunizeau, Moran & Friston, 2009). Parameters of two linear models were estimated with the data of the 5 participants from which we obtained causal judgments. In model 1, we only included regressors representing the six conditions of interests (L-D, L-IC, L-INC, P-D, P-IC, and P-INC), response times, and head movements' parameters. Model 2 expanded the model 1 by including a regressor with the sign of causal judgments. With Bayesian analysis, we answered the following question: Which model has more probability of causing the hemodynamic response in our voxel of interest? Figure 5 shows the results. The model including the sign of causal judgments as a regressor did not perform better than our original model. Because the sign of causal judgments did not affect the neural response in our region of interest, we can be more confident that not having causal judgments from the other participants does not bias our interpretation of the entire data set.

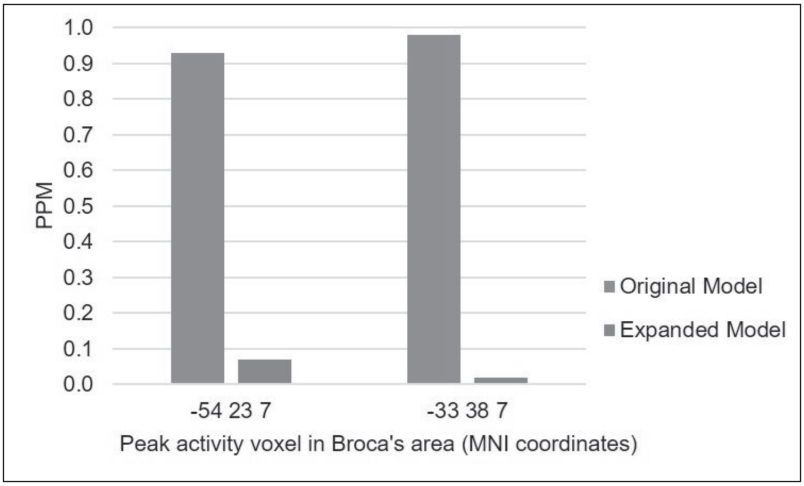

Figure 5. Results yielded by the posterior probability maps (PPM) of activity in two voxels of Broca's area. PPM were estimated in models with (expanded model) and without (original model) a regressor comprising causal judgments.

5. DISCUSSION

This study aimed at observing BOLD responses in Broca's area elicited during the processing of visual causal direct, causal indirect, and non-causal events that followed two different linguistic causal constructions, periphrastic and lexical causatives, presented in terms of verbal instructions. We found that, compared with the lexical condition (i.e., on lexical blocks), during the periphrastic condition (i.e., on periphrastic blocks) judgments of direct and indirect causal events activated respectively the pars triangularis and the pars opercularis whereas the evaluation of indirect non-causal events activated the pars triangularis. Furthermore, in the periphrastic condition, the processing of direct events more strongly activated the pars triangularis than the processing of indirect events.

Different psycholinguistic processes are associated with differential activity in Broca's area. Strong activity in Broca's area arises in conditions demanding semantic control (Whitney, Kirk, O'Sullivan, Lambon Ralph & Jefferies, 2011), effort (Wallentin, Roepstorff, Glover & Burgess, 2006), task difficulty (Binder, Desai, Graves & Conant, 2009; Ruff, Blumstein, Myers & Hutchison, 2008), working memory (Rogalsky & Hickok, 2011; Rogalsky, Matchin & Hickok, 2008), and semantic integration (Rappaport Hovav, Doron & Sichel, 2010). Interestingly, whereas previous works have reported this differential activity *during* the processing of linguistic structures, current data show differential activity in Broca's area *after* the processing of linguistic structures, during the processing of visual animations. This is, activity was detected during the15-s block that followed the 7-s window comprising the linguistic structure. This suggests that our linguistic constructions might have primed different perceptual contents, affecting the processing of visual stimuli.

The hypothesis of the linguistic priming of perceptual contents has been studied with the linguistic category priming paradigm (Semin, 2008). Recently, however Ijzerman, Regenberg, Saddlemyer and Koole (2015) reported a series of behavioral experiments that provided no evidence in support of this hypothesis at the level of *simple* sentence-category mapping. Specifically, to test the hypothesis, Ijzerman et al. (2015) relied upon the thesis that verbs represent local, specific, or concrete events whereas adjectives represent global or abstract events. In one representative experiment, participants read either a sentence regarding global perception (referred to as the *verb condition*) or a sentence regarding local perception (referred to as the *adjective condition*). After reading the sentence, participants performed a perceptual focus task. They were shown one target figure and two alternative figures. The target figure could represent either a global perceptual process or a local perceptual process. Participants had to choose the alternative figure that better matched the target. The hypothesis of a linguistic priming of perceptual contents predicted that the perceptual focus performance accuracy should be higher on congruent (e.g., global target in the verb condition) than on incongruent trials (e.g., global target in the adjective condition). Neither this experiment nor eight additional variants provided support to the linguistic category priming hypothesis. Ijzerman et al. (2015) concluded that at the level of simple categories the linguistic category priming hypothesis appears to be wrong. However, they suggested that linguistic constructions might prime different perceptual at the level of *more complex* perceptual relationships, raising the *complexity hypothesis*.

Within the context of the complexity hypothesis, we could conceptualize our billiards balls stimuli in terms of their perceptual or *relational* complexity, a framework that has been used in the study of the neural basis of abstract conceptualization (Badre, 2008; Badre & D'Esposito, 2007; Christoff & Gabrieli, 2000; Christoff & Keramatian, 2008; Christoff, Keramatian, Gordon, Smith & Mädler, 2009; Robin & Holyoak, 1995). In a visual stimulus, as the number of relations increases the order of the stimulus' relational complexity is said to increase. A closer comparison between our direct and indirect causal events reveals that whereas the direct event comprises one event, both the indirect causal and the indirect-non causal events comprises two events. Therefore, whereas causal judgment of direct launching only requires the detection of a first-order relational complexity, causal judgment of indirect events requires, first, the detection of two single causal events (i.e., two first-order relational complexities) and, second, the evaluation of the relation between these single events (i.e., a second-order relational complexity).

Crucially, the processing of low-order relational complexities is associated with activity in the ventrolateral prefrontal cortex (BAs 44, 45, 47) (Badre & D'Esposito, 2007; Christoff & Gabrieli, 2000; Christoff et al., 2009). Therefore, from the perspective of the complexity hypothesis (Ijzerman et al., 2015), periphrastic verbal instructions would drive the detection of low-order relational complexities during judgments of visual billiards balls collisions, being this processing associated with activity in Broca's area. Interestingly, we found that the activity in Broca's area was segregated between the pars opercularis (when participants judged indirect events) and the pars triangularis (when participants judged both direct and non-causal indirect events), suggesting that these subregions effectively connect (i.e., interact) (Friston, 2007) during causal judgments on periphrastic blocks.

From a decision making perspective, the dynamics of formal linear accumulator models (LBA) could provide some clues about the processes underlying the activity in Broca's area on periphrastic blocks. In the 2FCT, participants store linguistic-driven conceptual information in short term memory, maintain such information in memory while observing a testing probe, and decide whether or not the probe match the information in memory. LBA models of 2FCT account for this type of decision making process in terms of evidence accumulation against or in support of a decision (Brown & Heathcote, 2008). Two accumulators collect evidence in support and against the mismatch between a probe (e.g., the visual animation) and the information in memory (e.g., language-driven causal conceptualization). When cumulative evidence reaches one of the accumulators' decision thresholds, the system releases a response. We speculate, that the accumulation process on periphrastic blocks differs from the accumulation process on lexical blocks. This difference could be associated with increased activity in Broca's area on periphrastic blocks.

To conclude, current results suggest that causal judgment of visual events preceded by a periphrastic verbal instruction is a process segregated between the pars opercularis and the pars triangularis. However, the current univariate design and analysis do not inform about either functional (correlated activity) or effective (causal interregional) connectivity between both subregions. This motivates a future agenda aiming at identifying whether there is a functional connectivity between both the pars opercularis and the pars triangularis during the periphrastic condition, compared with the lexical condition. If the functional connectivity is identified, it would be worth investigating how both periphrastic and lexical verbal instructions modulate the effective connectivity between these subregions. Changes in the effective connectivity could be specifically investigated using dynamic causal modeling (Friston, 2007).

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