

Short Communication

Where the brain appreciates the final state of an event: The neural correlates of telicity

Domenica Romagno^a, Giuseppina Rota^b, Emiliano Ricciardi^{b,c,*}, Pietro Pietrini^b^a Department of Linguistics “T. Bolelli”, University of Pisa, Via S. Maria 36, 56126 Pisa, Italy^b Laboratory of Clinical Biochemistry and Molecular Biology, University of Pisa Medical School, Azienda Ospedaliero Universitaria Pisana “Santa Chiara”, Via Roma, 67 Bldg. 43, 56127 Pisa, Italy^c MRI Laboratory, Fondazione Toscana “Gabriele Monasterio” CNR/Regione Toscana, Via G. Moruzzi 1, 56124 Pisa, Italy

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ABSTRACT

In this study we investigated whether the human brain distinguishes between telic events that necessarily entail a specified endpoint (e.g., *reaching*), and atelic events with no delimitation or final state (e.g., *chasing*). We used functional magnetic resonance imaging to explore the patterns of neural response associated with verbs denoting telic and atelic events, and found that the left posterior middle temporal gyrus (pMTG), an area consistently engaged by verb processing tasks, showed a significantly higher activation for telic compared with atelic verbs. These results provide the first evidence that the human brain appreciates whether events lead to an end or a change of state. Moreover, they provide an explanation for the long-debated question of which verb properties modulate neural activity in the left pMTG, as they indicate that, independently of any other semantic property, verb processing and event knowledge in this area are specifically related to the representation of telicity.

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1. Introduction

In everyday life, we acquire knowledge of objects (e.g., animals and tools) and events (e.g., *walking* or *eating an apple*). In human languages, object concepts are typically conveyed by nouns, and event concepts by verbs. While a great deal has been learned about object concepts, and consistent findings on how the brain represents different object categories have been provided by neuropsychological and brain functional studies (Mahon & Caramazza, 2011; Ricciardi & Pietrini, 2011), the neural underpinnings of event concepts have yet to be clarified. Specifically, which properties are crucial to the representation of event concepts and thus modulate verb responsive brain areas still remains unsettled (Crepaldi, Berlinger, Paulesu, & Luzzatti, 2011; Vigliocco, Vinson, Druks, Barber, & Cappa, 2011). Neither motion features nor the degree of concreteness and imageability could consistently explain the representation of event concepts in the human brain (Bedny, Caramazza, Grossman, Pascual-Leone, & Saxe, 2008; Rodríguez-Ferreiro, Gennari, Davies, & Cuetos, 2011; Yu, Law, Han, Zhu, & Bi, 2011).

In this study, we tested the hypothesis that telicity modulates event-specific neural responses. Telicity is the property

distinguishing events that necessarily entail a specified endpoint (e.g., *reaching*, *arriving*) from events with no temporal and spatial delimitation, or final state (e.g. *chasing*, *staying*). The endpoint is an inherent part of the telic event, without which the event could not be what it is. Therefore, *reaching the top of a mountain* necessarily implies a final state; if that end state is not attained, then the top cannot be said to have been reached (Vendler, 1967).

Why should the telic/atelic distinction be captured in the brain? We may suppose that telicity carries an important evolutionary function, as the ability to appreciate whether events continuously unfold over time or, alternatively, lead to an end or a change of state is necessary for selecting appropriate behaviors to successfully meet environmental and social demands.

Telicity, indeed, plays a crucial role in language organization, change and acquisition, in both spoken and signed languages, independently of language-specific features (Grose, Wilbur, & Schalber, 2007; Slabakova, 2001). A large set of universal principles of complex mapping between semantics and morphosyntax is governed by telicity (Tenny, 1994). For instance, the auxiliary selection in the compound tenses of intransitive verbs in Italian – and in many other languages (Sorace, 2011) – is related to the degree of telicity of verbs: *arrivare* “to arrive” (telic) takes *essere* “to be” as auxiliary, whereas *camminare* “to walk” (atelic) takes *avere* “to have” (*essi sono arrivati* “they have arrived” vs. *essi hanno camminato* “they have walked”). Antinucci and Miller (1976) have shown that in the first past construction that Italian children acquire the auxiliary is lacking and the past participle agrees in gender and number

* Corresponding author at: Laboratory of Clinical Biochemistry and Molecular Biology, University of Pisa, Azienda Ospedaliero Universitaria Pisana “Santa Chiara”, Via Roma, 67 Bldg. 43, I-56127 Pisa, Italy. Fax: +39 050 993556.

E-mail address: emiliano.ricciardi@bioclinica.unipi.it (E. Ricciardi).

with the object (e.g., *Toto rotta bambola* = lit. “Toto broken doll”). The verbs occurring in this structure are only telic. At the same stage of development, atelic verbs do not occur in the past construction at all, but only in the present. Children are sensitive to the final resultant state of an event, as they use past tense markers as adjective markers by producing object agreement. The psychological reality of telicity is addressed in Romagno, Papagno, and Caramazza (2010). This study reports the case of a Semantic Dementia patient presenting a dissociation between a severely impaired access to the referential semantic features of verbs (dying, for instance, refers to stopping living or existing) and a perfectly spared access to more abstract semantic properties of verbs, including telicity. Furthermore, electrophysiological data suggested differential processing of telic and atelic verbs in specific sentence structures (Malaia, Wilbur, & Weber-Fox, 2009). However, whether and how telicity is represented in the brain has not yet been examined.

Because the distinction between telic and atelic events perfectly maps onto the distinction between telic and atelic verbs (Bertinetto, 1986), here we used functional magnetic resonance imaging (fMRI), in conjunction with verb stimuli, to covertly investigate whether the brain distinguishes between the two different categories of event, independently of any other verb feature.

It is well-known that telicity is involved in defining (or co-defining) unaccusativity (or split intransitivity, i.e., the division of intransitive verbs into two morphosyntactically distinct classes, unaccusative and unergative): telic one-argument verbs (e.g., “to arrive”), indeed, tend to show an unaccusative morphosyntactic behavior, either within or across languages (Alexiadou, Anagnostopoulou, & Everaert, 2004; Sorace, 2000; Sorace, 2004; Sorace, 2011; Van Valin, 1990). Moreover, prior studies have shown distinctive neuropsychological patterns associated with unaccusative verbs (Bastiaanse & Van Zonneveld, 2005; Kegl, 1995; Kim & Thompson, 2004; Lee & Thompson, 2004). Therefore, in order to disentangle telicity, as conceptual-semantic property, from unaccusativity, here we used both one argument (e.g., “to arrive”) and two argument (e.g., “to build”) telic verbs, and excluded both variable behavior verbs, such as “to run”, and verbs with alternating transitivity, such as “to burn”. Specifically, we included only inherently telic verbs, that is, verbs whose telicity was not determined at the verb phrase level, but by the verb lexeme itself (Tenny, 1994; Vendler, 1967; Verkuyl, 1972). This was particularly relevant, because stimuli presented during the encoding phase of the experimental procedure were verb infinitives in isolation.

Specifically, in a delayed match-to-sample task, four telic or atelic Italian verb infinitives were presented sequentially during an encoding phase and sequentially followed by a maintenance gap and the presentation of a probe stimulus (an inflected verb form), after which the individual task response was collected. Verbs represent unbiased stimuli as opposed to pictures that, being included within a delimited frame, might intrinsically drive a telic interpretation even when the represented event is actually atelic in nature (e.g., a picture of someone *walking*). Competing semantic, sensorimotor and emotional features were thoroughly controlled for, in order to isolate the role of telicity in modulating neural responses to verbs.

We hypothesize that telicity modulates neural activity in brain areas that have been most consistently implicated in semantic and lexical aspects of verb processing (Bedny, Caramazza, Pascual-Leone, & Saxe, 2011; Bedny et al., 2008; Shetreet, Friedmann, & Hadar, 2010). Specifically, we predict a preferential response to telic verbs because the information of necessarily entailing a specified endpoint is additional. This clearly appears in the Logical Structure (LS) of verbs, i.e., the formal representation of verb semantics (Dowty, 1979; Van Valin, 1990; Van Valin & LaPolla, 1997). Both state and activity atelic verbs correspond to semantic primitives,

which are homogeneous and, therefore, not decomposable in subevents, and represent building blocks for semantic representation of other verb classes. Telic verbs, instead, are not homogeneous and have a more complex LS. The atelic activity verb “to chase”, for instance, may be represented as **activity**’ (x,y): *John chased the dog* = **chase**’ (John, dog). The atelic state verb “to exist” may be represented as **state**’ (x): *this exists* = **exist**’ (this). The telic verb “to build”, instead, denotes an activity that causes a change of state of argument (y), which goes from the state of non-existence to the state of existence: **activity**’ (x,y) – cause – become **state**’ (y). Therefore, *John built a house* may be represented as **build**’ (John, house) – cause – become **exist**’ (house).

Moreover, telic verbs appears to be the more prototypical members of verb category, as defined on semantic grounds (Hopper & Thompson, 1984; Hopper & Thompson, 1985; Langacker, 1987; Sasse, 2001; Vogel & Comrie, 2000, among many others).

Finally, the analysis of the different phases of the match-to-sample task will address whether the two verb categories recruit perceptual or cognitive resources differentially. We expect telicity to modulate brain responses during stimulus encoding only, with no effect on the other working memory processes.

2. Results

2.1. Behavioral results

Participants remained unaware of the real aim of the study. During the fMRI session, group mean performance accuracy was $95 \pm 0.05\%$ (\pm SD), and group mean reaction times (RTs) were 810.03 ± 207.30 ms (\pm SD). No significant differences in either accuracy or RTs were found between telic and atelic state verbs ($T_{(1,21)} = -1.86$, $p = 0.08$ and $T_{(1,21)} = -1.29$, $p = 0.21$, respectively; paired t -test), between telic and atelic activity verbs ($T_{(1,21)} = -0.59$, $p = 0.56$ and $T_{(1,21)} = -0.91$, $p = 0.37$, respectively) or between atelic state and atelic activity verbs ($T_{(1,21)} = 0.56$, $p = 0.58$ and $T_{(1,21)} = 0.44$, $p = 0.66$, respectively).

2.2. fMRI results

2.2.1. Whole brain comparison between verb classes

In a mixed-effect meta-analysis, a significantly (whole brain corrected $p < 0.01$) greater response for telic as compared to atelic verbs was found in the left posterior middle temporal gyrus (pMTG; Talairach coordinates: $-55, -54, 0$; BA22/37), only during the verb encoding phase (Fig. 1A). No other differences between telic and atelic verbs were found during the encoding phase. At the same significance level, no differences were found during the maintenance gap.

2.2.2. Telicity effect in verb-selective ROIs

As reported in Table 1 and Fig. 1B, among all brain areas defined *a priori* on the basis of findings from previous brain functional studies, which determined the cortical structures showing a significantly higher response to verbs compared with nouns during semantic judgment tasks (Vigliocco et al., 2011), a modulation of telicity was found in the left posterior middle temporal ROI during the encoding phase only. None of the other frontal, temporal or parietal ROIs showed any modulation of response.

3. Discussion

The results of this study indicate that the human brain implicitly distinguishes between telic and atelic events, as neural activity in the left pMTG was differentially modulated by telic and atelic

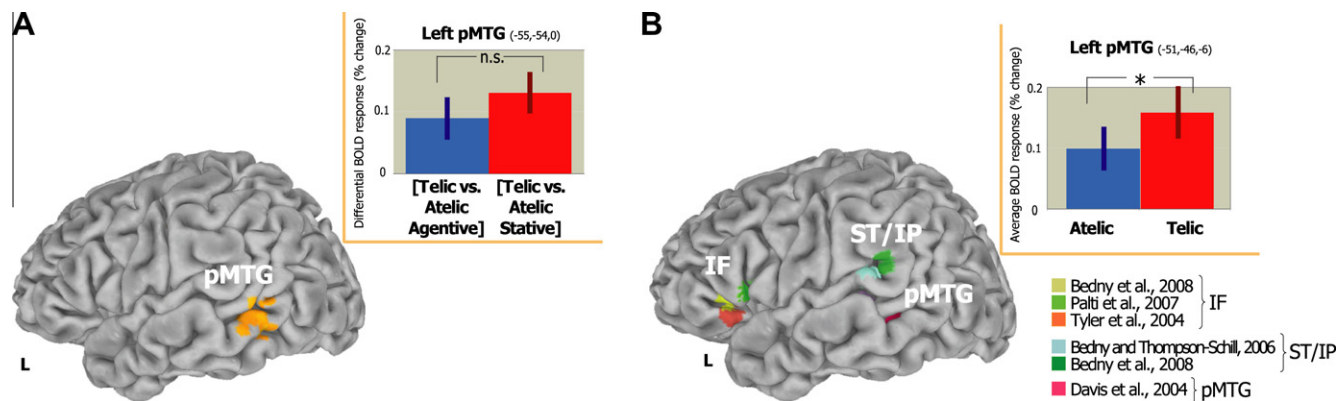


Fig. 1. (A) Statistical map showing significant differences between telic and atelic verb classes during the encoding phase. Spatially normalized activations are projected onto a single-subject, left-sided brain surface template in Talairach space. Bar graphs illustrate group differential BOLD % changes \pm SE for the [telic vs. atelic state] (in red) and [telic vs. atelic activity] (in blue) contrasts in the significant cluster of left posterior middle temporal gyrus (pMTG). (B) Spatially normalized ROIs of verb-selective activations reported in previous imaging studies (Table 1) are projected onto a single-subject, left-sided brain surface template in Talairach space. Color legends and references are reported for those ROI spheres that are visible on the surface. Bar graphs illustrate group average BOLD % changes \pm SE for the telic (red) and atelic (blue) verbs in the significant cluster of left posterior middle temporal gyrus (pMTG). IF: inferior frontal; ST/IP: superior temporal/inferior parietal.

Table 1
Coordinates of verb-selective activations reported in previous imaging studies, and evaluation of the specific modulation of telicity in *a priori* selected regions of interest.

Source	Brain areas	Talairach atlas coordinates ^a			Telicity vs. atelicity contrast ^b	
		x	y	z	Encoding	Maintenance
Tyler et al., 2004	Left inferior frontal	-49	16	10	1.70; n.s.	-0.52; n.s.
	Left inferior frontal	-38	21	-1	0.12; n.s.	-0.92; n.s.
	Left inferior frontal	-46	22	4	-0.05; n.s.	-0.29; n.s.
Bedny & Thompson-Schill, 2006	Left posterior cingulate	-9	-34	21	0.85; n.s.	1.01; n.s.
	Left superior temporal	-56	-37	16	1.25; n.s.	-0.07; n.s.
Davis, Meunier, & Marslen-Wilson, 2004	Left posterior middle temporal	-53	-47	-3	2.77; <0.012	-0.47; n.s.
Palti, Ben-Shachar, Hendler, & Hadar, 2007	Left inferior frontal	-47	7	13	0.23; n.s.	-0.60; n.s.
	Left posterior middle frontal	-25	11	46	0.66; n.s.	-0.41; n.s.
	Left superior temporal sulcus	-53	-35	5	1.07; n.s.	-1.44; n.s.
Bedny et al., 2008	Left superior temporal/inferior parietal	-61	-42	21	0.53; n.s.	1.35; n.s.
	Left inferior frontal	-51	21	-1	-1.17; n.s.	0.59; n.s.
	Right middle/superior temporal	61	-31	3	-0.60; n.s.	-0.17; n.s.

^a As converted from MNI Atlas to Talairach Coordinated under the AFNI GUI.

^b T-scores and *p*-values; bold fonts highlight significant ($p < 0.05$) contrasts.

verbs after all the other semantic components had been controlled for and in spite of the lack of any behavioral difference.

The left pMTG has been robustly and consistently implicated in verb processing across a variety of studies, tasks and languages (Perani et al., 1999; Shapiro, Moo, & Caramazza, 2006; Willms et al., 2011; Yokoyama et al., 2006). However, which verb features drive the recruitment of this region has long baffled neurocognitive scientists. Whether the left pMTG responds preferentially to the grammatical category of verb, as established on formal (morpho-syntactic) grounds (Tyler, Bright, Fletcher, & Stamatakis, 2004; Tyler, Randall, & Stamatakis, 2008), or, rather, to certain event properties paralleling verb semantic features (Kable, Kan, Wilson, Thompson-Schill, & Chatterjee, 2005; Rodríguez-Ferreiro et al., 2011) has not yet been solved (Crepaldi et al., 2011; Vigliocco et al., 2011).

The left pMTG has also been implicated in conceptual action knowledge (Campanella, D'Agostini, Skrap, & Shallice, 2010; Kable et al., 2005; Kalenine, Buxbaum, & Coslett, 2010; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995), and evidence of a semantic, rather than morphosyntactic, representation of verbs in this region has been recently provided by studies involving tasks which required semantic but not morphosyntactic processing of verbs and nouns (Bedny et al., 2008; Bedny et al., 2011). Moreover, patients

with left pMTG lesions are impaired in semantic judgement on both verbs and pictures of actions (Kemmerer, Rudrauf, Manzel, & Tranel, 2010; Tranel, Kemmerer, Adolphs, Damasio, & Damasio, 2003). However, neither the amount of concreteness, motor activity and visual-motion features which the event entails nor the distinction between mental states and imageable actions modulate event and verb-specific neural responses in the left pMTG (Bedny et al., 2008; Yu et al., 2011).

What kind of conceptual information reflected in verb semantics does left pMTG represent?

Our results provide the first evidence that neural activity in the left pMTG is modulated by telicity, and thus indicate that event knowledge and verb processing in this region are specifically related to the representation of telicity. These findings raise the possibility that left pMTG represents conceptual semantic properties of verbs, and specifically that kind of conceptual information which is relevant to morphosyntax, as telicity, unlike referential semantic features, and independently of them, governs morphosyntax in a specified way (Dowty, 1979; Levin & Rappaport Hovav, 1995; Sorace, 2000; Sorace, 2011; Tenny, 1994; Van Valin, 1997). These observations may also explain findings from previous studies that have not directly assessed the representation of telicity. It has been found that the so-called unaccusative (i.e. *to arrive*) and unergative

(i.e. *to walk*) verbs are associated with different patterns of neural response (Shetreet & Friedmann, 2012; Shetreet et al., 2010). Moreover, agrammatic subjects showed difficulty in producing both unaccusative verbs, as compared to unergatives, and unaccusative constructions relative to transitive constructions of verbs with alternating transitivity, such as “to burn” and “to break” (Bastiaanse & Van Zonneveld, 2005; Kegl, 1995; Kim & Thompson, 2004; Lee & Thompson, 2004). These findings have been interpreted as related to the more complex syntactic operations associated to unaccusative verbs, which is consistent with agrammatic patients’ lesions in the left inferior frontal cortex, and may explain the left Inferior Frontal Gyrus (IFG) response to unaccusative verbs (Bastiaanse & Van Zonneveld, 2005; Shetreet et al., 2010).

Our results suggest that differences in verb production (Lee & Thompson, 2004) or in the patterns of neural response (Shetreet & Friedmann, 2012; Shetreet et al., 2010) between unergative and unaccusative verbs may be related to the effect of telicity, since unaccusatives are typically telic, as opposed to unergatives, typically atelic (Jezek, 2000; Levin & Rappaport Hovav, 1995). Interestingly, the left pMTG is one of the regions involved in processing unaccusative verbs and, unlike the left IFG, which has been linked to the syntactic operations associated with unaccusative verbs, appears to be involved in the semantic and lexical aspects of processing unaccusative verbs (Shetreet et al., 2010).

Which principles underlie unaccusativity phenomena has been largely debated (Sorace, 2011; Bentley, 2006; Levin & Rappaport Hovav, 1995; Van Valin, 1990; Burzio, 1986; Perlmutter, 1978; Perlmutter, 1989; Rosen, 1984, among many others). Evidence for the distinction between unaccusative and unergative verbs is both morphosyntactic and semantic. The most consistent and comprehensive account claims that unaccusativity is morphosyntactically encoded but semantically determined (Alexiadou et al., 2004; Levin & Rappaport Hovav, 1995; Sorace, 2000; Sorace, 2004; Sorace, 2011; Van Valin, 1990). The hypothesis of a split intransitivity hierarchy, primarily defined by telicity (and the related notion of subject affectedness), and secondarily by the degree of agentivity of the verb (Jezek, 2000; Sorace, 2000; Sorace, 2004; Sorace, 2011) may also account for the unaccusative mismatches, i.e. cases of verbs showing a variable morphosyntactic behavior either within or across languages (Dowty, 1979; Levin & Rappaport Hovav, 1995; Rosen, 1984). These observations suggest that the unaccusativity effect in the left pMTG is related to semantic differences between unaccusative and unergative verbs. Our results support this hypothesis, as they provide a clear evidence of a telicity effect in the left pMTG, independently of any other verb properties, including the number of core arguments of verbs. Specifically, the telic stimuli used in the present experiment include both one-argument and two-argument verbs (i.e., inherently telic transitive verbs). The left pMTG activation associated with telic transitive verbs cannot be accounted for as caused by an unaccusativity syntactic effect: unaccusative verbs, in fact, are intransitive.

Damage to the left pMTG often results in impaired verb production and comprehension (Aggujaro, Crepaldi, Pistarini, Taricco, & Luzzatti, 2006; Tranel, Adolphs, Damasio, & Damasio, 2001). Disrupted telicity processing, following lesions across the left pMTG, may contribute to explain behaviors in which the ability to appreciate the endpoint of an event seems deficitary, as in the case of patients with semantic deficits (Patterson, Nestor, & Rogers, 2007), or with goal directed and non-goal directed wandering (Rolland et al., 2007). Significantly, among the previously identified verb-selective networks, left pMTG was the only region showing a telicity effect (Table 1).

In the present study, volunteers were instructed to pay attention to each verb presented in sequence and to respond by button pressing when a match with the following probe was detected. This paradigm allowed us to make our volunteers attend the

stimulus material without having them engaged in any specific verb processing task nor making them aware of the real aim of the study, thus isolating the neural substrates of covertly processing telic and atelic verbs. Of note, our results showed that the brain distinguishes between telic and atelic verbs during stimulus encoding, but the two verb categories do not recruit working memory resources differentially, as shown by the lack of any significant difference in the left pMTG response between telic and atelic verbs during the maintenance phase.

In conclusion, our results show that the human brain operates the telic/atelic distinction in a cortical area involved in verb processing. Delimited events with a measurable outcome modulate brain activity differently from undelimited events with no change of state. Importantly, such a modulation is independent of any competing sensorimotor and semantic properties, including concreteness, imageability, dinamicity, agentivity, durativity, animacy and number of arguments of verbs. Furthermore, telicity is independent of the physical motion components of verbs (Bedny et al., 2011; Wallentin, Højlund Nielsen, Vuust, Dohn, et al., 2011), and identifies event types separately from referential semantics, pragmatic representations and sensorimotor features, which were not found to drive the neural substrate mediating event knowledge and verb processing (Bedny et al., 2008; Yu et al., 2011).

4. Materials and methods

4.1. Participants

Twenty-two [6F; age (mean \pm SD): 28 ± 5 years; education: 19.6 ± 2.5 years], right-handed native Italian volunteers participated in the study. None of them had any medical, neurological or psychiatric condition that could affect brain function or development, nor had been taking any medication for at least 4 weeks prior to the study. All participants had normal or corrected-to-normal visual acuity. The study was conducted under a protocol approved by the Ethical Committee at the University of Pisa Medical School (Protocol no. 1616/2003). All volunteers gave their written informed consent after the study procedures and potential risks had been explained.

4.2. Stimuli

Trials were grouped in blocks to compare patterns of neural response following implicit processing of inherently telic and atelic Italian verb infinitives, matched for cumulative frequency (663.01 ± 813.75 (mean \pm SD); $p = 0.81$, Kruskal Wallis), word length in letters (8.36 ± 1.72 ; $p = 0.94$) and number of core arguments (Thompson et al., 2007): on this score, we included both one-argument verbs, such as *to walk*, and two-argument verbs, such as *to chase*. The number of arguments of the verbs was matched across conditions. The rates of frequency and length were based on Bertinetto et al. (1995). In order to isolate the role of telicity in modulating neural activity, we also controlled for the potential effect of competing semantic verb properties (i.e., dinamicity, agentivity, durativity). Telic verbs such as *to reach* and *to build* are dynamic: in fact, the achievement of a goal and the change of state necessarily imply dinamicity. To disentangle the telic/atelic distinction from the dynamic/non-dynamic distinction, atelic stimuli included both dynamic verbs (activities, such as *to walk* and *to chase*) and non-dynamic verbs (states, such as *to possess* and *to believe*). In addition, telic verbs may be either agentive, like *to leave*, whose subject does have the control of the event, or non-agentive, like *to recover*, whose subject does not have the control of the event. In order to disentangle telicity from agentivity, we used both

atelic agentive verbs (activities, such as *to talk*) and atelic non-agentive verbs (prototypical states, such as *to exist*). Finally, durativity refers to the extent of time involved in the event that the verb denotes. Since all the atelic stimuli allowed for a durative interpretation, telic stimuli did not include the so-called semelfactive verbs, such as *to blink*, that are necessarily instantaneous and, therefore, unlikely to occur in a durative interpretation (Van Valin, 1997). Furthermore, to rule out the animacy of the subject of verbs as a potential confound in the neural response, we only included verbs whose subject may correspond to animate entities. In summary, we used three sets of 20 stimuli: telic verbs (e.g., *arrivare* “to arrive”, *partire* “to leave”, *costruire* “to build”, *demolire* “to demolish”), atelic states (e.g., *esistere* “to exist”, *possedere* “to possess”, *significare* “to mean”, *stare* “stay”) and atelic activities (e.g., *inseguire* “to chase”, *camminare* “to walk”, *parlare* “to talk”, *accarezzare* “to caress”). Stimuli were also matched for valence (6.30 ± 1.35 ; $p = 0.076$) and arousal (4.24 ± 1.12 ; $p = 0.055$). To this end, a large set of verbs ($N = 81$) had been previously rated by a distinct group of healthy native Italian volunteers [$N = 30$; 11F; age: 29 ± 3 years, education: 18.2 ± 3.03 years], by using the Self-Assessment Mannequin Scale (Bradley & Lang, 1994). Only balanced material was included in the experiment. According to our experimental design and functional data analysis, as detailed below, telicity was the only feature distinguishing telic verbs from the two classes of atelic verbs (Table 2).

4.3. Task

Volunteers performed a delayed match-to-sample task that covertly assessed the representation of telicity. The task encompassed three subsequent phases: encoding (8 s), maintenance (7 s) and recall (5.5 s). During the encoding phase, four infinitives were presented sequentially for 1.5 s each and separated by a white screen (0.5 s each). Each set of infinitives was followed by a 7 s-maintenance gap (while volunteers viewed a fixation cross), a 1.5 s-presentation of a probe stimulus consisting of an inflected verb form (e.g., [*they*] *talk*) and a 4 s-interval to collect individual responses. We included one condition (i.e. verb category) per block. Volunteers were instructed to pay attention to verbs, and asked to indicate whether or not the probe matched one of the four infinitives included in the previous block, by pressing a button

with their right or left thumb, respectively, within 4 s. Stimuli presentation was randomized within and across participants, with the limitation of keeping a fixed ratio of 30% matching rate between probe and stimuli. Hence, non-matching rate between the probe and the preceding verbs was 70% in every condition. Therefore, each condition was equally likely to occur along the duration of the run, and with different sets of verbs. In each experimental run trials were presented in 10 blocks alternated with 15 s baseline. The task was repeated for 60 blocks (20 blocks per verb class), across six different runs. Stimuli were written words presented visually on a rear projection screen visible inside the scanner through a mirror. We performed stimulus presentation and collected behavioral responses using E-prime 1.1 (Psychology Software Tools, Inc., Sharpsburg, PA).

4.4. Data acquisition and analysis

The experiment was performed using a 1.5 Tesla whole body scanner (General Electric, Milwaukee, WI). Gradient echo echoplanar images (TR = 2500 ms, 33 slices, 4-mm-thick axial images, FOV = 24 cm, TE = 30 ms, flip angle = 90° , voxel size = $3.75 \text{ mm} \times 3.75 \text{ mm} \times 4 \text{ mm}$) as well as high-resolution T1-weighted spoiled gradient recall images (124 slices, 1.2-mm-thick sagittal images, FOV = 24 cm) to be used as anatomical references were acquired. Six time series of 148 brain volumes, accordingly to the experimental design, were obtained.

Statistical analysis of behavioral data obtained during the match-to-sample task was performed by using the statistical package SPSS 13.0 (SPSS Inc., Chicago, IL).

AFNI and SUMA packages (<http://afni.nimh.nih.gov/afni>) were used to perform data preprocessing and statistical analysis, and to display results. First, all the experimental runs were concatenated, performing a rigid-body motion correction, slice scan time correction, and spatial smoothing (3D Gaussian filter, FWHM = 4 mm). Second, functional data were normalized by computing mean intensity values of each voxel, and by dividing the value within each voxel by its mean to estimate the percent signal change at each time point. One subject was excluded due to head movement artifacts.

Brain activity elicited during all the phases of the delayed match-to-sample task (encoding, maintenance, probe presentation and response) was examined. A multiple regression analysis was performed, by modeling three regressors for each semantic property of interest (i.e., telicity, atelic state, atelic activity) in the encoding and maintenance phases, one regressor for probe presentation and one regressor for response, thus resulting in eight regressors of interest. The six movement parameters from the volume registration, and the polynomial regressors accounting for baseline shifts and linear/quadratic drifts in each scan series were included in the analysis as regressors of no interest. Within individual multiple regression analysis, general linear tests (GLTs) were modeled to extract magnitude response for each single task and semantic components, and for both [telic vs. atelic state] and [telic vs. atelic activity] contrasts. We transformed individual unthresholded magnitude response maps into the Talairach and Tournoux Atlas coordinate system (Talairach & Tournoux, 1988), and applied a voxel isometric 3 mm resampling for group analyses.

A mixed-effect meta-analysis (3dMEMA) identified patterns of activation within experimental conditions, and assessed differences between verb classes during the encoding and maintenance phases. In order to compare telic vs. atelic verb processing, volumes of interest were restricted to significantly task-activated regions during either the encoding or maintenance phase (as defined by a within condition one-sample *T*-test, FDR corrected q value < 0.025), and the [telic vs. atelic state] and [telic vs. atelic activity] GLT coefficients were analyzed in a one-sample *T*-test,

Table 2
Semantic, sensorimotor and emotional features of the telic and atelic verb stimuli employed in the fMRI experimental paradigm.

Controlled features	Telic verbs ^a	Atelic verbs ^a	
		States	Activities
Telicity	+	–	–
Dynamicity	±	–	+
Agentivity	±	–	+
Durativity	+	+	+
Animacy	+	+	+
Concreteness	±	–	+
Imageability ^b	±	–	+
Number of Arguments	=	=	=
Length	=	=	=
Frequency	=	=	=
Valence	=	=	=
Arousal	=	=	=

^a +, – and ± indicate the presence/absence of the specified feature. = refers to the matching results.

^b In a post-scanning session, imageability (I) and concreteness (C) ratings (mean ± SD) were collected from the 22 volunteers for all stimuli. The ratings confirmed the distinct features of telic verbs ($I = 5.17 \pm 0.80$, $C = 4.59 \pm 0.94$), atelic states ($I = 3.53 \pm 0.75$, $C = 2.92 \pm 0.91$), and atelic activities ($I = 5.87 \pm 0.66$, $C = 5.33 \pm 0.85$) (Bates, Burani, D'Amico, & Barca, 2011).

accordingly with our rationale that telicity was the only feature distinguishing telic verbs from the two classes of atelic verbs as detailed in Table 2. As compared to a conventional T-contrast, the mixed-effect meta-analysis takes into account within-subject response variability of an activated brain region and assigns each subject's contribution (from the individual T statistics of each stimulus timeseries regression model) to the final result based on a weighted instead of an equal treatment (Chen, Saad, & Cox, 2010).

The correction of group analyses across task-activated regions was made by using Monte-Carlo simulations, run via AlphaSim with a voxelwise threshold of 0.005 that resulted in a minimum cluster volume > 9 voxels, nearest-neighbor, for a corrected p value < 0.01 at cluster level. Finally, individual BOLD signal percent change for the [telic vs. atelic state] and [telic vs. atelic activity] contrast values were extracted from brain regions differentially activated by telic and atelic verbs as obtained by the mixed-effect meta-analysis (Fig. 1A).

During the recall phase, presumably, a number of concurrent cognitive processes took place. Volunteers engaged in (1) retrieval of the stored information, (2) match to sample comparisons between what they remembered and the presented probe, (3) decision making processes (did they match or not?). Probes had a 30% rate of positive match. The very low number of positive matches available per condition, together with the multiple concurring cognitive processes, makes the recall phase poorly informative and its results of difficult interpretation. On this basis, we excluded the recall phase from further data analysis.

In order to strengthen our observation of a specific modulation of telicity, we *a priori* defined verb-selective ROIs by locating 5 mm-radius spheres on the coordinates of brain areas that have been reported in previous, independent functional studies assessing the specificity of activation for verb as compared to noun processing, as reported in Table 2 of Vigliocco et al., 2011. In order to reduce any task-related confound, we limited our selection to specific verb vs. noun contrasts and to semantic judgment tasks, which more similarly to the task used in the present study required participants to process the *denotatum* of the stimuli independently of any morphological processing or lexical decision device (Vigliocco et al., 2011). Individual parameter estimates for the responses to telic and atelic verbs (here averaged across state and agentive) were extracted from each ROI for the encoding and maintenance conditions, and compared with two-tailed paired Student T -tests. Contrast T scores and p values have been reported in Table 1.

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References

- Aggijaro, S., Crepaldi, D., Pistarini, C., Taricco, M., & Luzzatti, C. (2006). Neuro-anatomical correlates of impaired retrieval of verbs and nouns: Interaction of grammatical class, imageability and actionality. *J. Neurolinguist*, 19, 174–194.
- Alexiadou, A., Anagnostopoulou, E., & Everaert, M. (2004). *The unaccusativity puzzle: Explorations of the Syntax–Lexicon interface*. Oxford: Oxford University Press.
- Antinucci, F., & Miller, R. (1976). How children talk about what happened. *J. Child Lang.*, 3, 169–189.
- Bastiaanse, R., & Van Zonneveld, R. (2005). Sentence production with verbs of alternating transitivity in agrammatic Broca's aphasia. *J. Neurolinguist*, 18, 59–66.
- Bates, E., Burani, C., D'Amico, S., & Barca, L. (2011). Word reading and picture naming in Italian. *Mem. Cognition*, 29, 986–999.
- Bedny, M., Caramazza, A., Grossman, E., Pascual-Leone, A., & Saxe, R. (2008). Concepts are more than percepts: The case of action verbs. *J. Neurosci.*, 28, 11347–11353.
- Bedny, M., Caramazza, A., Pascual-Leone, A., & Saxe, R. (2011). Typical neural representations of action verbs develop without vision. *Cereb. Cortex* (Advance access published, June 7, 2011).
- Bedny, M., & Thompson-Schill, S. L. (2006). Neuroanatomically separable effects of imageability and grammatical class during single-word comprehension. *Brain Lang.*, 98, 127–139.
- Bentley, D. (2006). *Split Intransitivity in Italian*. Berlin/New York: Mouton de Gruyter.
- Bertinetto, P.M. (1986). *Tempo, aspetto e azione nel verbo italiano*. Firenze: Accademia della Crusca.
- Bertinetto, P.M., Burani, C., Laudanna, A., Marconi, L., Ratti, D., Rolando, C., & Thornton, A. (1995). *Corpus e Lessico di Frequenza dell'Italiano Scritto (CoLFIS)*.
- Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: The self-assessment manikin and the semantic differential. *J. Behav. Ther. Exp. Psychol.*, 25, 49–59.
- Burzio, L. (1986). *Italian Syntax: A Government-Binding Approach*. Dordrecht: Foris.
- Campanella, F., D'Agostini, S., Skrap, M., & Shallice, T. (2010). Naming manipulable objects: Anatomy of a category specific effect in left temporal tumours. *Neuropsychologia*, 48, 1583–1597.
- Chen, G., Saad, Z.S., & Cox, R.W. (2010). Modeling multilevel variance components and outliers in group analysis. In *Proceedings of the 16th annual meeting of the organization for human brain mapping* (pp. 43). Minneapolis: Organization for Human Brain Mapping.
- Crepaldi, D., Berlinger, M., Paulesu, E., & Luzzatti, C. (2011). A place for nouns and a place for verbs? A critical review of neurocognitive data on grammatical-class effects. *Brain Lang.*, 116, 33–49.
- Davis, M. H., Meunier, F., & Marslen-Wilson, W. D. (2004). Neural responses to morphological, syntactic, and semantic properties of single words: An fMRI study. *Brain Lang.*, 89, 439–449.
- Dowty, D. (1979). *Word meaning and montague grammar*. Dordrecht: Reidel.
- Grose, D., Wilbur, R. B., & Schalber, K. (2007). Events and telicity in classifier predicates: A reanalysis of body part classifier predicates in ASL. *Lingua*, 117, 1258–1284.
- Hopper, P., & Thompson, S. A. (1984). The discourse basis for lexical categories in universal grammar. *Language*, 60, 703–752.
- Hopper, P., & Thompson, S. A. (1985). The iconicity of the universal categories "noun" and "verb". In J. Haiman (Ed.), *Iconicity in syntax* (pp. 151–183). John Benjamins: Amsterdam-Philadelphia.
- Jezek, E. (2000). Classi verbali e composizionalità: Il caso della doppia inaccusatività in italiano. In *Classi di parole e conoscenza lessicale. Special Issue of Studi Italiani di Linguistica Teorica e Applicata*, 2, pp. 289–310.
- Kable, J. W., Kan, I. P., Wilson, A., Thompson-Schill, S. L., & Chatterjee, A. (2005). Conceptual representations of action in the lateral temporal cortex. *J. Cogn. Neurosci.*, 17, 1855–1870.
- Kalenine, S., Buxbaum, L. J., & Coslett, H. B. (2010). Critical brain regions for action recognition: Lesion-symptom mapping in left hemisphere stroke. *Brain*, 133, 3269–3280.
- Kegl, J. (1995). Levels of representation and units of access relevant to agrammatism. *Brain Lang.*, 50, 151–200.
- Kemmerer, D., Rudrauf, D., Manzel, K., Tranel, D. (2010). Behavioral patterns and lesion sites associated with impaired processing of lexical and conceptual knowledge of actions. *Cortex*.
- Kim, M., & Thompson, C. K. (2004). Verb deficits in Alzheimer's disease and agrammatism: Implications for lexical organization. *Brain Lang.*, 88, 1–20.
- Langacker, R. W. (1987). *Foundations of cognitive grammar: Theoretical prerequisites*. Stanford, CA: Stanford University Press.
- Lee, M., & Thompson, C. K. (2004). Agrammatic aphasic production and comprehension of unaccusative verbs in sentence contexts. *J. Neurolinguist*, 17, 315–330.
- Levin, B., & Rappaport Hovav, M. (1995). *Unaccusativity: At the syntax–lexical semantics interface*. Cambridge MA/London: The MIT Press.
- Mahon, B. Z., & Caramazza, A. (2011). What drives the organization of object knowledge in the brain? *Trends Cogn. Sci.*, 15, 97–103.
- Malaia, E., Wilbur, R. B., & Weber-Fox, C. (2009). ERP evidence for telicity effects on syntactic processing in garden-path sentences. *Brain Lang.*, 108, 145–158.
- Martin, A., Haxby, J. V., Lalonde, F. M., Wiggs, C. L., & Ungerleider, L. G. (1995). Discrete cortical regions associated with knowledge of color and knowledge of action. *Science*, 270, 102–105.
- Palti, D., Ben-Shachar, M., Hendler, T., & Hadar, U. (2007). The cortical correlates of grammatical category differences: An fMRI study of nouns and verbs. *Hum. Brain Mapp.*, 28, 303–314.
- Patterson, K., Nestor, P. J., & Rogers, T. T. (2007). Where do you know what you know? The representation of semantic knowledge in the human brain. *Nat. Rev. Neurosci.*, 8, 976–987.
- Perani, D., Cappa, S. F., Schnur, T., Tettamanti, M., Collina, S., Rosa, M. M., et al. (1999). The neural correlates of verb and noun processing. A PET study. *Brain*, 122, 2337–2344.
- Perlmutter, D. M. (1978). Impersonal passives and the unaccusative hypothesis. *BLS*, 4, 157–189.
- Perlmutter, D. M. (1989). Multiattachment and the unaccusative hypothesis: The perfect auxiliary in Italian. *Probus*, 1, 63–119.
- Ricciardi, E., & Pietrini, P. (2011). New light from the dark: What blindness can teach us about brain function. *Curr. Opin. Neurol.*, 24, 357–363.
- Rodríguez-Ferreiro, J., Gennari, S. P., Davies, R., & Cuetos, F. (2011). Neural correlates of abstract verb processing. *J. Cogn. Neurosci.*, 23, 106–118.
- Rolland, Y., Andrieu, S., Cantet, C., Morley, E., Thomas, D., Nourhashemi, F., et al. (2007). Wandering behavior and Alzheimer disease. The REAL. FR prospective study. *Alzheimer Dis. Assoc. Disord.*, 21, 31–38.

- Romagno, D., Papagno, C., & Caramazza, A. (2010). Evidence from neuropsychology on verb features: The case of a patient with Semantic Dementia. In P.M. Bertinetto, A. Korhonen, A. Lenci, A. Melinger, S. Schulte im Walde, & A. Villavicencio (Eds.), *The identification and representation of verb features – Proceedings of verb 2010, Interdisciplinary workshop on verbs* (pp. 182–187). Pisa: SNS.
- Rosen, C. (1984). The interface between semantic roles and initial grammatical relations. In D. M. Perlmutter & C. Rosen (Eds.), *Studies in relational grammar* (pp. 38–80). Chicago: University of Chicago Press.
- Sasse, H. J. (2001). Scales between nouniness and verbiness. In M. Haspelmath et al. (Eds.), *Language typology and language universals. An international handbook* (pp. 495–509). Berlin/New York: De Gruyter.
- Shapiro, K. A., Moo, L. R., & Caramazza, A. (2006). Cortical signatures of noun and verb production. *Proc. Natl. Acad. Sci. USA*, 103, 1644–1649.
- Shetreet, E., & Friedmann, N. (2012). Stretched, jumped and fell: An fMRI investigation of reflexive verbs and other intransitives. *Neuroimage*, 60, 1800–1806.
- Shetreet, E., Friedmann, N., & Hadar, U. (2010). The neural correlates of linguistic distinctions: Unaccusative and unergative verbs. *J. Cogn. Neurosci.*, 22, 2306–2315.
- Slabakova, R. (2001). *Telicity in the second language*. Amsterdam/Philadelphia: Benjamins.
- Sorace, A. (2000). Gradients in auxiliary selection with intransitive verbs. *Language*, 76, 859–890.
- Sorace, A. (2011). Gradience in split intransitivity: The end of the unaccusative hypothesis. *Arch. Glottol. Ital.*, 96, 67–86.
- Sorace, A. (2004). Gradience at the lexicon–syntax interface. Evidence from auxiliary selection. In A. Alexiadou, M. Everaert, & E. Anagnostopoulou (Eds.), *The unaccusativity puzzle* (pp. 243–268). Oxford: Oxford University Press.
- Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain: 3-Dimensional proportional system – an approach to cerebral imaging*. New York: Thieme Medical Publishers.
- Tenny, C. (1994). *Aspectual roles and the syntax–semantics interface*. Dordrecht/Boston/London: Kluwer.
- Thompson, C. K., Bonakdarpour, B., Fix, S. C., Blumenfeld, H. D., Parrish, T. B., Gitelman, D. R., et al. (2007). Neural correlates of verb argument structure processing. *J. Cogn. Neurosci.*, 19, 753–1767.
- Tranel, D., Adolphs, R., Damasio, H., & Damasio, A. R. (2001). A neural basis for the retrieval of words for actions. *Cogn. Neuropsychol.*, 18, 655–674.
- Tranel, D., Kemmerer, D., Adolphs, R., Damasio, H., & Damasio, A. (2003). Neural correlates of conceptual knowledge for actions. *Cogn. Neuropsychol.*, 20, 409–432.
- Tyler, L. K., Bright, P., Fletcher, P., & Stamatakis, E. A. (2004). Neural processing of nouns and verbs: The role of inflectional morphology. *Neuropsychologia*, 42, 512–523.
- Tyler, L. K., Randall, B., & Stamatakis, E. A. (2008). Cortical differentiation for nouns and verbs depends on grammatical markers. *J. Cogn. Neurosci.*, 20, 1381–1389.
- Van Valin, R. D. Jr., (1990). Semantic parameters of split intransitivity. *Language*, 66, 221–260.
- Van Valin, R. D., Jr., & LaPolla, R. J. (1997). *Syntax: Structure, meaning and function*. Cambridge: Cambridge University Press.
- Vendler, Z. (1967). Verbs and times. In *Linguistics in philosophy* (pp. 97–121). Ithaca: Cornell University Press.
- Verkuyl, H. (1972). *On the compositional nature of the aspects*. Dordrecht: Reidel.
- Vigliocco, G., Vinson, D. P., Druks, J., Barber, H., & Cappa, S. F. (2011). Nouns and verbs in the brain: A review of behavioural, electrophysiological, neuropsychological and imaging studies. *Neurosci. Biobehav. Rev.*, 35, 407–426.
- Vogel, P., & Comrie, B. (2000). *Approaches to the typology of word classes*. Berlin: Mouton de Gruyter.
- Wallentin, M., Højlund Nielsen, A., Vuust, P., Dohn, A., Roepstorff, A., & Ellegaard Lund, T. (2011). BOLD response to motion verbs in left posterior middle temporal gyrus during story comprehension. *Brain Lang.*, 119, 221–225.
- Willms, J. L., Shapiro, K. A., Peelen, M. V., Pajtas, P. E., Costa, A., Moo, L. R., et al. (2011). Language-invariant verb processing regions in Spanish–English bilinguals. *Neuroimage*, 57, 251–261.
- Yokoyama, S., Miyamoto, T., Riera, J., Kim, J., Akitsuki, Y., Iwata, K., et al. (2006). Cortical mechanisms involved in the processing of verbs: An fMRI study. *J. Cogn. Neurosci.*, 18, 1304–1313.
- Yu, X., Law, S. P., Han, Z., Zhu, C., & Bi, Y. (2011). Dissociative neural correlates of semantic processing of nouns and verbs in Chinese – A language with minimal inflectional morphology. *Neuroimage*, 58, 912–922.