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Abstract

The aim of this study was to specify the role of action representations in thematic and functional similarity relations between manipulable artifact objects. Recent behavioral and neurophysiological evidence indicates that while they are all relevant for manipulable artifact concepts, semantic relations based on thematic (e.g., saw-wood), specific function similarity (e.g., saw-axe) and general function similarity (e.g., saw-knife) are differently processed, and may relate to different levels of action representation. Point-light displays of object-related actions previously encoded at the gesture-level (e.g., "sawing) or at higher-level of action representation (e.g., "cutting") were used as primes before participants identified target objects (e.g., saw) among semantically related and unrelated distractors (e.g., wood, feather, piano). Analysis of eye movements on the different objects during target identification informed about the amplitude and timing of implicit activation of the different semantic relations. Results showed that action prime encoding impacted the processing of thematic relations, but not that of functional similarity relations. Semantic competition with thematic distractors was greater and earlier following action primes encoded at the gesture-level compared to action primes encoded at higher level. As a whole, these findings highlight the direct influence of action representations on thematic relation processing, and suggest that thematic relations involve gesture-level representations rather than intention-level representations.

Keywords

Action priming, Thematic relations, Functional similarity relations, Manipulable artifact concepts, Eye-tracking

1. Introduction

A large body of evidence now indicates that manipulable object concepts rely, at least partially, on motor representations. Semantic processing of visually-presented objects or words induces motor resonance, as reflected by stimulus-response compatibility effects (Bub, Masson, & Cree, 2008; Tucker & Ellis, 2001). Several studies further demonstrate that a concurrent motor task can interfere with object conceptual processing, suggesting that motor resonance has a functional role in object identification (Witt, Kemmerer, Linkenauger, & Culham, 2010; Yee, Chrysikou, Hoffman, & Thompson-Schill, 2012). In addition to single object concepts, motor representations likely support certain semantic relations between manipulable objects. Priming effects have been reported between objects that share manipulation features (Helbig, Graf, & Kiefer, 2006; Labeye, Oker, Badard, & Versace, 2008; Myung, Blumstein, & Sedivy, 2006), and objects with similar manipulation can interfere with each other in semantic tasks at both the trial (Lee, Middleton, Mirman, Kalénine, & Buxbaum, 2013) and block level (Campanella & Shallice, 2011; Watson & Buxbaum, 2014). Motor resonance is also critical for manipulation similarity processing between objects, which can be disrupted by a concurrent motor task (Downing-Doucet & Guérard, 2014). Overall, the involvement of motor (i.e. object-related gesture) representations in single manipulable artifact concepts and manipulation similarity relations has been clearly demonstrated. However, the importance of motor representations for other kinds of semantic relations between manipulable artifacts, in particular those based on functional knowledge, is still largely debated. Accordingly, the general aim of the present study was to advance our understanding of the role of action in processing semantic relations between manipulable artifact objects.

Data from apraxic patients (Buxbaum & Saffran, 2002) and healthy adults (Garcea & Mahon, 2012) show dissociations between manipulation and function similarity judgments, suggesting that functional relations between objects do not heavily rely on action representations. Yet other interpretations may be considered. First, functional relations between objects are not only defined in terms of functional *similarity* (e.g., saw-axe, both used to cut wood; tape-glue, both used to fix things together). Thematic relations referring to spatial/temporal *contiguity* between objects may correspond to another type of functional relations between objects. Objects that are directly used together (e.g., saw-wood, tape-paper) are thematically related, but not functionally *similar* a priori. Those thematic relations are particularly relevant for manipulable artifact concepts. Several studies indicate that they are processed more quickly as compared to other types of semantic relations between manipulable artifacts (Borghi, Flumini, Natraj, & Wheaton, 2012; Kalénine & Bonthoux, 2008; Kalénine et al., 2009). Motor representations, at least if they refer to object-related gesture representations, may support thematic relations to a greater extent than functional similarity relations. In a recent study Tsagkaridis, Watson, Jax, & Buxbaum (Tsagkaridis, Watson, Jax, & Buxbaum, 2014) showed that patients with gesture recognition deficits do not show any categorization preference for thematically-related objects that are directly used together (e.g., wine bottle-corkscrew), in contrast to healthy adults and patients with no such impairment. Consistent with this finding, Yoon, Humphreys, & Riddoch (Yoon, Humphreys, & Riddoch, 2010) showed that healthy participants were faster to judge that two objects could be used together when objects were correctly positioned for action. Thus, we can hypothesize that activation of gesture representations underlie processing of thematic relations for manipulable artifacts. Second, action may be represented at different hierarchical levels (Cooper & Shallice, 2006; Hamilton & Grafton, 2007; van Elk, van Schie, & Bekkering, 2014) including gestures (e.g., specific grasping movement), action goals (e.g., bring a cup to the mouth), and intentions (e.g., drink). Functional similarity relations may be more related to higher levels of action representations corresponding to the actor's intention (e.g., saw and axe are functionally similar if one wants to cut wood) rather than to gesture-level representations. This may explain why they dissociate with manipulation similarity relations. Together, the recent studies in the domain of action and object semantics suggest that action representations may be also involved in processing thematic and functional similarity relations between objects. However, action involvement may be visible at different representational levels, with thematic relations recruiting gesture-level representations ("sawing" gesture) and functional similarity relations relying on higher-level action representations ("cutting " intention). In this work, we focused on the relationship between different levels of action representations on the one hand, and thematic and functional similarity relations between objects on the other hand.

In previous studies (Kalénine, Mirman, Middleton, & Buxbaum, 2012; Pluciennicka, Coello, & Kalénine, submitted) we assessed incidental processing of thematic and functional similarity relations during object identification among distractors using eye tracking in the Visual World Paradigm. Participants had to localize a target object in a 4-picture display in response of the target name orally provided. Eye fixations on the different objects were recorded from auditory target name onset until visual target object identification. Distractors objects could be semantically related or unrelated to the target. In such paradigm, related distractors typically compete for attention and receive more fixations than non-related objects. Competition reflects activation of the properties that objects have in common. In these previous studies, the semantically related distractor present in the display could be related in 3 different ways depending on the condition. It could share a thematic relation with the target (broom-dustpan) or it could be functionally similar to the target at a more specific (e.g. broom-vacuum cleaner, *to clean the floor*) or more general (broom-sponge, *to clean the house*) level. When target names were provided in isolation (Kalénine et al., 2012), the 3 types of related distractors equally competed for attention, but with different time courses. Specifically, competition with thematic distractors was earlier and more transient than competition with functionally similar distractors, in particular at the general level, confirming the advantage for thematic relation processing among semantic relations between manipulable artifacts (see Borghi et al., 2012; Kalénine & Bonthoux, 2008; Kalénine et al., 2009; Tsagkaridis et al., 2014), even when the task does not require explicit identification of those relations. Note that congruent timing differences were observed at the neurophysiological level with the same stimuli (Wamain, Pluciennicka, & Kalénine, 2015). Importantly, competition effect temporal dynamics were modulated by context in Kalénine et al. (Kalénine et al., 2012), Experiment 2. Target names were embedded in verbal contexts that presented lower-level or higher-level action intentions (e.g. "he wanted to clean the floor" vs "he wanted to clean the house"). Competitions effects with functionally similar distractors were boosted by action intentions presented at the corresponding level of representation. For instance, "he wanted to clean the house" facilitated processing of general functional similarity relations such as "broom-sponge". However, verbal action intentions had no impact on thematic competition. One interpretation of the absence of thematic processing modulation was that thematic relations rely on action representations at the gesture-level, and not at the intention-level. In the present study, we specifically addressed this issue by testing the influence of gesture activation on thematic and functional similarity processing using the same eye-tracking paradigm. Point-light displays presenting object use gestures and meaningless dot patterns served as primes and were displayed before target object visual search. Gesture primes were expected to modulate semantic competition between thematically-related objects, and possibly to a certain extent functionally similar objects. Moreover, we hypothesized that the direction of action priming (i.e., facilitation versus interference) could be further influenced by the level of representation of gesture primes. To assess this hypothesis, we also manipulated point-light-display encoding prior to the eye-tracking experiment.

2. Methods

2.1. Participants:

Forty adults (mean age= 23.0 years, SD=3.8 years) took part in the experiment. All participants were native French speakers and had normal or corrected-to normal vision. All provided written informed consent. The study was approved by the Local Ethics Committee of Human Sciences and was in conformity with the 2008 Helsinki Declaration.

2.2. Materials:

Picture and audio stimuli were the same as the ones used in a previous eye-tracking study (Pluciennicka, Coello & Kalenine, submitted), and are presented below.

2.2.2. Picture stimuli

A total of 84 object color photographs were used as picture stimuli. They included 14 reference object pictures, 42 semantically related and 28 unrelated object pictures. Semantic related pairs were further divided into 3 Semantic Displays, with 14 related pairs in each condition. In the Thematic displays, the reference object *could be used with/upon* the related object (e.g. saw is *used with/upon* wood, frying pan is *used with/upon* butter). In the Specific Function displays, objects were *functionally similar* at a relative *specific level* (e.g., saw and axe *could both be used to cut wood,* frying pan and sauce pan *could both be used to warm up food*). In the General Function displays, objects were *functionally similar* at a relative *general level* (e.g., saw and knife *could both be used to cut, frying pan and cake mold are both used to cook*). For semantically unrelated object pairs, half was visually similar (by color, form or size) to the reference object and half was visually dissimilar. One hundred and thirty-five supplementary pictures were used for practice and filler trials. All the images were scaled to a maximum size of 200 x 200 pixels such as at least one dimension was 200 pixels.

Semantic relations between objects were selected from a large property generation study (Pluciennicka, Coello, & Kalénine, 2014) that ensured a distinction between the 3 types of semantic relations. In our property generation task, properties were prompted with sentences such as “[NAME] can be used with/upon [BLANK]” and “[NAME] can be used to [BLANK]”. Thematic relations were defined as object pairs that regularly appear together in the “[NAME] can be used with/upon [BLANK]” sentences in participants’ productions. Functional similarity relations were defined as two concepts that received a similar response after "[NAME] can be used to [BLANK]" prompts. Note that functional similarity relations that also appeared thematically related in the generation task were excluded. Objects functionally similar at the specific level were also related at the more general level (e.g. *"can be used to cut"* has been generated in response to saw, axe, and knife), but objects functionally similar at the general level were not similar at the specific level (e.g.*"can be used to cut wood"* has been only generated in response to saw and axe, not knife).

Several control measures were also collected on the stimuli (cf. Pluciennicka, Coello & Kalenine, submitted). Picture name agreement (i.e. "determine whether you agree with the name provided for this object") reached 99%. Visual and manipulation similarity between target pictures and their corresponding related and unrelated primes[1] were evaluated using a 7-point Likert scale. Twelve additional participants (who did not participate in the present experiment) were asked to rate to what extend two objects of a pair 1) were visually similar 2) could be manipulated in the same way. The 3 types of semantic relations were overall equivalent in terms of visual similarity [F(2,26)= 0,54, p=.59]. Semantically unrelated but visually similar primes were judged more visually similar to the target than visually dissimilar unrelated primes [F (1,13)= 16.12, p<.001], but were equivalent to semantically related objects in terms of visual similarity [F(1,13)= 1.76, p=.21]. Similarly, the 3 types of semantic relations were not significantly different in terms of manipulation similarity [F(2,26)= 2.78, p=.08 ; no significant pairwise difference between semantic relations]. Indices of overall semantic relatedness were based on Latent Semantic Analysis (LSA) measures extracted from text corpora. Semantically related objects received a high cosine value, which confirmed that all types of related pairs were highly related. Moreover, degree of overall semantic relatedness was greater for semantically related object pairs than unrelated object pairs [F(1,13)= 200.4, p<.001], but not significantly different between thematic, specific function, and general function relations [F(2,26)= 2.76, p=.08]. In other words, object pairs in the 3 semantic conditions were all highly related but in different ways. See Appendix for a full list of stimuli and their mean normative values.

[1] The number of semantically unrelated and visually dissimilar prime pictures has been doubled in the present experiment in comparison to Pluciennicka et al. submitted. The norms reported here only concern the initial set of unrelated primes. However, the second set has only been added to keep the design balanced and has not been included in the analyses.

2.2.3. Audio stimuli

A total of 70 object name recordings were used as audio stimuli. They included 14 reference object names (critical trials) and 54 non-critical target object names (filler trials). They were recorded by a native French female speaker with help of Audacity open source software. Average duration of target object names was 699 ms (SD=170 ms). All sounds were digitized at 44 KHz and their amplitude was normalized. Seven additional object name recordings were used for practice.

2.2.4. Point Light Displays

A total of 28 one-second point-light-display (PLD) movies were used as prime stimuli. Fourteen object-related actions were recorded with Qualisys motion capture system (Qualysis AB, Gothenburg, Sweden), one for each reference object. Eighteen reflective markers were attached to the major joints of the body of an actor (shoulder, elbow, wrist, thumb, index finger, hip, knee, foot, head and plexus). Motion of these markers was then recorded to create movies of black 'point-light' displays (PLD) against a white background. This resulted in 14 Action Primes presenting minimal object-related action information. Note that whereas the actions were performed with the objects, objects were not equipped with markers and were therefore not visible on the prime movie.

Fourteen Meaningless Primes were also designed from the 14 PLDs. They were designed by applying a random transformation on the x coordinate of each marker before applying a 180° spatial rotation to the movie. Thus, Meaningless Primes were equivalent to Action Primes in terms of movement characteristics (duration, number of points and kinematic of points) but did not convey any signification. Four additional PLDs (2 supplementary Action Primes and their Meaningless Primes) were also designed for practice trials.

2.3. Experimental design

For each of the 14 reference objects, 3 critical 4-image displays were designed. Critical displays included the reference object as target (e.g., saw), one semantically related distractor (e.g., knife), a semantically unrelated but visually similar distractor (e.g., feather), and one semantically unrelated and visually dissimilar distractor (e.g., piano). Semantically related distractors could be thematically related (e.g., wood), share a specific function (e.g., axe) or share a general function (e.g., knife) with the target. Each critical display was presented twice during the experiment, once with the corresponding Action Prime and once with the corresponding Meaningless Prime. Thus, there were 14 reference objects x 3 Semantic Displays x 2 Prime Types leading to 84 critical trials.

Filler trials were also designed to avoid potential strategies based on picture and/or association repetition. Eighty-four "composed filler" trials involved the same objects as critical trials but on those trials, the reference object was never the target. Displays on "composed filler" trials were presented twice following their corresponding primes, either with the same prime (i.e. twice with the Action Prime or twice with the Meaningless Prime) or with a different prime (i.e., once with Action Prime and once with Meaningless Prime). Twenty-eight unrelated filler trials used novel displays involving unrelated pictures. In those displays, one of the pictures was presented twice as target, preceded either by an Action Prime or a Meaningless Prime. Overall, an experimental session lasted about 40 minutes and corresponded to 208 trials presented in one block, including 12 practice trials and 196 experimental trials randomly presented.

Prior to the eye-tracking experiment, participants were assigned to one of two experimental groups, in which action primes were presented following two distinct Encodings. In the Gesture-Level encoding group, the 14 Action Prime PLDs were presented twice using E-prime software (Psychological Software Tools, Pittsburgh, PA, USA), and participants were simply asked to observe them carefully. In the High-Level encoding group, Action Primes PLDs were explicitly associated with a high-level action representations in a preliminary learning session. A sentence describing a high-level action representation was orally provided before each PLD (e.g. "this is someone cutting something" followed by the sawing PLD, see Appendix 1). After two presentations of the 14 sentences-PLDs associations, PLDs were presented a last time followed by the corresponding sentence. Finally, the associations between PLDs and high-level action representations were checked by asking participants to provide the verbal sentence associated with each PLD presented in random order. Association was considered learned when participants provided the correct action verb (e.g., sawing gesture = "cut"). After the Action Prime encoding phase, the two groups performed the same eye-tracking experiment. The full design of the study is presented in Figure 1.

[Figure 1 about here]

Figure 1. Design of the critical trials. Reference objects were targets presented among distractors in 3 possible semantic displays. Semantic displays were primed either by

meaningless primes or by action prime. Action primes had been previously encoded either at the gesture-level or at the high-level depending on the group. Fixation proportions on the different Objects in the display were contrasted as a function of Prime Type, Semantic Display and Encoding.

2.4. Eye-tracking procedure

Participants were seated in front of the 17-inch computer screen (resolution: 1024 x 768 pixels) with theirs eyes approximately at a distance of 23.5-inches from the screen, so that each picture subtended about 5.1 degrees of visual angle. They had to clink on the fixation cross presented in the center of the screen to start each trial. First, the prime PLDs were displayed for 1000 ms within a 500 × 500 pixels area in the center of the screen, followed by a 4-image preview for the next 1000 ms. Then 200 ms before the offset of the preview, a red circle was presented in the center of the screen to drive attention back to the central location. After the short picture preview, participants heard the target word through speakers, and had to move the mouse pointer on the image that corresponded to the target word and click on the picture. The trial procedure is presented in Figure 2. Stimulus presentation and response were monitored with E-prime. Eye movements were recorded from 4-image display onset to mouse click using EyeLink 1000 desktop in remote position sampling at 500 Hz. Overall, the duration of the experiment was about 40 minutes.

[Figure 2 –in color in the WEB version- about here]

Fig. 2: Example of trial used the in eye-tracking experiment. First, the 1000 ms point-light display was shown. Then the display including the target object (e.g., saw), a semantically related distractor (e.g., axe), a visually similar distractor (e.g., feather) and an unrelated distractor (e.g., piano) was presented. Target words were delivered after a 1000-ms preview of the display (including a 250-ms red dot at the end of preview).

3. Data Analysis

3.1 Areas of interest

Following previous studies (Kalénine et al., 2012; Pluciennicka et al., submitted) we defined 4 areas of interest (AOI) around the object pictures, which corresponded to 400 x 300 quadrants in the four corners of the screen. Fixations that fell into one of the AOIs were considered as object fixations whereas fixations that fell out of the AOIs were non-object fixations. Fixation proportion of each AOI could be either 0 or 1 at any point of time since the participant fixated either a give object or not. Proportion of fixations on each AOI was calculated over every 50 ms time bin and translated into proportion of fixations on each type of distractor objects, referring to semantic distractor, visually similar unrelated distractor, and non-visually similar unrelated distractor. Time course estimate of fixations on each object was achieved by averaging data from critical trials over all items and all participants.

As we previously found that visual similarity influenced participant's gaze pattern in the Visual World Paradigm (Pluciennicka et al., submitted), comparison of fixation proportions between semantically related and unrelated objects were computed using the semantically unrelated but visually similar object as baseline in all analyses.

3.1 Time Windows of interest

Two distinct time windows were selected for analysis of gaze data (Kalénine et al., 2012). After presentation of the PLD primes but before word onset, we could expect anticipatory fixations on the different objects – including target, semantically related and unrelated distractors- during picture preview. Thus, we designed an Anticipation Window between 200 ms and 1000 ms after picture presentation (from the first saccade possibly driven by the pictures to word onset, see Figure 2). Fixation proportion over the Anticipation Window were analyzed as a function of 3 x Object (Target, Related distractor, Unrelated distractor), 3 x Semantic Display (Thematic, Specific Function, General Function), 2 x Prime Type (Meaningless Prime, Action Prime) as within-subject factors, and 2 x Encoding (Gesture-level, High-level) as between-subject factor.

After word onset, we expected the semantically related distractor to compete for attention with the target during its identification. This competition is visible in the difference in fixation curves towards related versus unrelated distractors, and not on target fixation curve that will rise until reaching asymptote. Thus, the analyses in the Competition Window after word onset focused on semantically related and unrelated distractors. Moreover, combining the Visual World Paradigm with priming required to adjust the boundaries of the Competition Window according to condition. For instance, shifts in target fixation asymptote could be expected after action compared to meaningless primes. Thus, we used remote competition windows of 600 ms time-locked on target fixation proportion asymptote in each condition (cf. Figure 3). Target fixation asymptote was determined by identifying the first of 5 consecutive 50 ms time bins with no more than 5% fixation increase (i.e. time bin before fixation plateau on target was reached). Target fixations were not further used in the analyses on the Competition Window, where fixation proportion was analyzed as a function of 2 x Object (Related distractor, Unrelated distractor), 3 x Semantic Display (Thematic, Specific Function, General Function), 2 x Prime Type (Meaningless Prime, Action Prime) as within-subject factors, and 2 x Encoding (Gesture-level, High-level) as between-subject factor.

3.3 Growth Curve Analysis of gaze data

As in previous studies (Kalénine et al., 2012; Pluciennicka et al., submitted), we used Growth Curve Analysis (GCA) for modeling and analysis of fixation curves. GCA is a multilevel modeling approach well suited to analysis of change over time, and particularly relevant for analysis of fixation time courses (see Mirman, 2014 for detailed description of the approach, advantages and recommendations). GCA allows capturing both amplitude and fined-grained time course differences between groups and/or conditions. The overall fixation curves were modeled using 4-order orthogonal polynomials (see Kalénine et al., 2012; Lee, Mirman, & Buxbaum, 2014; Mirman & Graziano, 2012; Mirman & Magnuson, 2009).The intercept reflects average overall fixation proportion (i.e. the overall height of the curve) and captures competition differences in *amplitude*. The other terms reflect the shape of the curve and capture competition differences in *timing (earlier/later competition)*. More particularly, the linear term reflects the steepness of the slope, the quadratic term describes the sharpness of the central peak, and the cubic and quartic terms capture the sharpness of the off-centered peaks. The random effect structure included overall variations of subjects and variations of subjects as a function of within-subject conditions on intercept, linear, quadratic, cubic, and quartic terms. Fixed effects corresponded to the different factors of interest and were incrementally added to the model on all time terms. In particular, we considered fixed effects of Object, Semantic Display, Prime type, and Encoding, alone and in interaction with each other. The impact of fixed effects on model fit was evaluated using a model comparison approach. Models were fit using Maximum Likelihood Estimation and improvement in model fit was assessed using -2LL deviance statistics (minus 2 times log-likelihood), which is distributed as χ^2 with k degrees of freedom corresponding to the k parameters added. T-tests on individual parameter estimates were then performed to evaluate specific differences between conditions. Normal approximation was used to determine parameter-specific p-values. All analyses were carried out in R version 2.14.2 using the lme4 package (Bates, Maechler, Bolker, & Walker, 2013).

3.4 Predictions

In the Anticipation Window, effects were mainly expected on the intercept term; reflecting differences in the overall amount of anticipatory fixations over the preview period before word onset. Precisely, we might expect a main effect of Object, but more importantly, we predicted an interaction between Object and Prime Type. This interaction may be further modulated by Semantic Display and/or Encoding:

1. After seeing Action Primes, Target objects (and possibly Related objects) would receive more anticipatory looks than Unrelated objects. This effect may be stronger for one condition of Encoding and/or one type of Semantic Display.

2. In contrast, after Meaningless Primes the overall proportion of anticipatory fixations should not differ between objects, regardless of Semantic Display and/or Encoding.

In the Competition Window, effects were expected on the amplitude (intercept) and/or time course (linear, quadratic, cubic and quartic terms) of the competition effect. We might also expect a main effect of Object. Crucially, we predicted a 4-way interaction between Object, Semantic Display, Encoding, and Prime Type.

1. With Action Primes, the 3-way interaction between Object, Semantic Display, and Encoding was expected to be significant. In particular, there should be a different pattern of Object x Encoding interaction in the different Semantic Displays:

- Competition effects with thematic competitors should be stronger and/or earlier when action primes were encoded at gesture-level, as compared to when action primes were submitted to high-level encoding (i.e., Object x Encoding interaction after Action Primes in Thematic Displays).
- In contrast, competition effects with General Function competitors (and possibly Specific Function competitors) should be stronger and/or earlier when action primes were encoded at the high-level than at the gesture-level of action representation.

2. With Meaningless primes, we could anticipate a significant main effect of Object and Object x Semantic Display interaction, but we did not expect any interaction with Encoding.

4. Results

4.1 Accuracy and reaction times

Statistical analyses were performed exclusively on the critical trials where target objects were correctly identified, and action primes correctly associated with high-level action representations (in the High-level encoding group). Target identification accuracy reached 99.5%, and action prime identification during High-level encoding was 76%. Overall, 12% of the data were excluded. Mean correct reaction time was 2341 ms (SD= 210). There was no effect of Semantic Display [$F(2,76)=1.75$, $p=0.18$] or Encoding [$F(1,38)=0.70$, $p=0.40$], but a significant effect of Prime Type [$F(1,38)=33.35$, $p <.001$], and a significant Prime Type x Semantic Display Interaction [$F(2,76)=4.02$, $p <.05$], see Table 1.

Table 1: Mean correct target identification times (mouse click) and standard deviations (SD) as a function of Prime Type and Semantic Displays.

	Action Primes	Meaningless Primes
General Function Displays	2278 ms (SD = 200)	2435 ms (SD = 299)
Specific Function Displays	2320 ms (SD = 200)	2371 ms (SD = 172)
Thematic Displays	2282 ms (SD = 175)	2363 ms (SD = 158)
All displays	2293 ms (SD = 191)	2389 ms (SD = 219)

4.2 Anticipation Window results

Model comparison showed a main effect of Object [χ^2 (10)= 71.11, $p< .001$]. As predicted, results revealed a significant Object x Prime Type interaction [χ^2 (10)= 49.69, $p< .001$; and Figure 2]. There was also a significant Object x Prime Type x Encoding interaction [χ^2 (10)= 26.41, $p< .005$]. In the Action Prime condition, the main effect of Object and the interaction between Object and Encoding were significant [χ^2 (10)= 89.94, $p< .001$ and χ^2 (10)=

22.67, p< .05 respectively, Table 2]. Target objects were more anticipated than unrelated objects, regardless of encoding or semantic display (intercept estimate= 0.093, t=4.30, p < .001). Target object fixation curves also differed from unrelated object fixation curves on linear and quartic time terms (linear estimate= 0.247, t=3.77, p < .001; quartic estimate= -0.101, t =-3.34, p< .005). Anticipatory differences between Encodings were not visible in the amount of anticipatory fixations on target objects (intercept estimate= -0.043, t=-1.43, p = .15). Model fit improvement after adding the Object x Encoding interaction in the Action Prime condition was due to a few differences in target anticipatory fixation time course compared to unrelated fixation curve (linear estimate= -0.021, t=-2.38, p < .05; quartic estimate= 0.135, t=3.28, p < .005).

In the Meaningless Prime condition, the main effect of Object was significant (χ^2 (10)= 18.59, p< .05). However, the amount of anticipatory fixations did not differ between objects (target intercept estimate= 0.030, t=1.56 p = .12, competitor intercept estimate= 0.007, t=0.39, p = .69; see Figure 2). A few timing differences were observed between target and competitor on the one hand (linear estimate: 0.170, t= 2.87, p < 005), and unrelated objects on the other hand (linear estimate: 0.126, t= 2.13, p < 05), probably reflecting curve differentiation between objects at the end of the preview period.

Table 2: Model fit and parameter estimates of anticipatory fixations in the Action Prime condition.

Anticipatory Fixation Model Comparison in the Action Prime condition*			
	LL	χ^2	p-value
base	8380	NA	NA
Object	**8425**	**89.95**	**<.001**
Encoding	**8432**	**13.98**	**.015**
Semantic Display	8436	7.50	.677
Object x Semantic Display	8445	16.68	.673
Object x Encoding	**8459**	**22.67**	**.012**
Semantic Display x Encoding	8456	6.23	.796

Object x Semantic Display x Encoding	8474 29.46 .0791	
** lmer structure of the Object x Semantic Display x Encoding model in each Prime Condition: (intercept+linear+quadratic+cubic+quartic)*(Object *Semantic Display * Encoding) +(intercept+linear+quadratic+cubic+quartic|Participant) +(intercept+linear+quadratic+cubic+quartic|Participant :Object :Semantic Display)*		
Parameter estimates related to the significant main effect of Object on anticipatory fixation time course in the Action Prime condition		
	Target vs. Unrelated	Competitor vs. Unrelated
	Estimate SE t-value	Estimate SE t-value
Intercept	**0.093 0.022 4.30**	-0.009 0.022 -0.453
Linear	**0.247 0.065 3.77**	-0.043 0.065 -0.666
Quadratic	0.021 0.046 0.457	0.017 0.046 0.362
Cubic	-0.040 0.042 -0.958	-0.027 0.042 -0.634
Quartic	**-0.101 0.030 -3.340**	-0.044 0.030 -1.444

[Figure 3 about here]

Fig. 3: Mean fixation proportion to the target, semantically related, and visually similar unrelated distractor as a function of time since picture display onset averaged across Semantic Displays and Encodings for Meaningless Prime (left) and Action Prime (right) conditions. Target name was delivered at 1000ms. The grey frames highlight the portion of the curve considered for statistical analysis of anticipatory and competition effects.

4.3 Competition Window results

As predicted, model comparison highlighted a main effect of Object [χ^2 (5)= 13.87, p<.05], and crucially, a significant 4-way interaction between Object, Semantic Display, Encoding, and Prime type [χ^2 (10)= 20.42, p<.05]. With Action Primes, Object interacted with

Semantic Display and Encoding [χ^2 (10)= 22.84, p< .05, see Table 3]. In Thematic displays, the Object x Encoding interaction reached significance [χ^2 (5)= 15.35, p< .01], but not in the Specific and General Function displays [χ^2 (10)= 6.60, p< .25 and χ^2 (10)= 1.48, p< .91, respectively]. As visible on the model fit presented in Figure 4, Gesture and High-Level Action Representation encodings had the opposite effect on the competition effect with Thematic competitors. This was reflected by important competition effect differences in amplitude (intercept estimate=-0,056, t=-2.09, p < .05) and timing (cubic estimate=0.067, t=2.12, p < .05; quartic estimate = 0.071, t = 2.893, p < .005). As mentioned earlier, cubic and quartic estimates usually capture early and late curve differences. Thus, competition in Thematic displays was greater and earlier when action primes were encoded at the Gesture-level compared to High-level of action representation. With Meaningless Primes, there was a trend towards a main effect of Object [χ^2 (10)= 9.75, p=.08], but no more fixations on competitor than unrelated objects overall (intercept estimate competitor-unrelated: 0.011, t= 0.57, p = 56). Moreover, Object did not interact with Semantic Display alone [χ^2 (10)= 12.05, p=.28] or in combination with Encoding, in contrast to Action prime condition [Object x Semantic Display x Encoding interaction: χ^2 (10)= 8.56, p=.57].

[Figure 4 about here]

Fig. 4: Model fit (lines) of the fixation data (points =means: error bars=individual standard errors) from the competition time window for General Function (left), Specific Function (Middle), and Thematic (right) displays when action primes were encoded at the gesture-level (top) or at the high-level of action representation (bottom).

Table 3: Model fit and parameter estimates of anticipatory fixations in the Action Prime condition.

Competition Fixation Model Comparison in the Action Prime condition*			
	LL	χ^2	p-value

base	4549 NA NA
Object	4554 9.52 .090
Encoding	4558 7.37 .194
Semantic Display	4564 12.22 .271
Object x Semantic Display	4570 12.05 .282
Object x Encoding	4571 3.29 .655
Semantic Display x Encoding	4580 16.70 .081
Object x Semantic Display x Encoding	**4591 22.84 .011**

** lmer structure of the Object x Semantic Display x Encoding model: (intercept+linear+quadratic+cubic+quartic)*(Object * Semantic Display*Encoding) +(intercept+linear+quadratic+cubic+quartic|Participant) +(intercept+linear+quadratic+cubic+quartic|Participant :Object : Semantic Display)*

Parameter estimates related to the significant Object x Encoding interaction for Thematic Displays in the Action Prime condition

	(Competitor vs. Unrelated) - (High-level vs Gesture-level encoding)		
	Estimate	SE	t-value
Intercept	**-0.056**	**0.027**	**-2.090**
Linear	0.002	0.072	0.033
Quadratic	0.034	0.043	0.777
Cubic	**0.067**	**0.033**	**2.012**
Quartic	**0.071**	**0.025**	**2.893**

Complementary analysis: bimanual versus unimanual object-related actions

Target objects and their semantic relations were chosen according to a previous property generation study. Thus, some objects may involve typical manipulation with the two hands (e.g. bowl) while other may involve mostly one hand (e.g. cup, see Appendix). In order to determine whether action priming effects on thematic processing could depend on this factor, we split items into bimanual and unimanual object-related actions (7 in each category). We performed a complementary analysis that incorporated the type of object-related actions (bimanual, unimanual) as within-subject factor in the model. The critical Object x Encoding interaction observed in Thematic displays preceded by Action primes was not modulated by the type of object-related actions [Object x Encoding: χ^2 (5)= 19.40, p< .005; Object x Encoding x Type of Object-Related Action: χ^2 (5)= 5.72, p< .33]. In other words, the pattern of opposite priming effects observed on thematic competition was similar for bimanual and unimanual object-related actions.

4. Discussion

In the present study, identification of manipulable artifact targets (e.g. saw) among distractors was primed with point-light displays presenting object-related actions or meaningless moving dots. Prior to the identification task, point-light displays of object-related actions were encoded at the level of gesture representation (« sawing ») or at a higher-level of action representation (« cutting » intention). Eye movements were recorded while participants searched for the target object in the picture display. Before target name onset, participants looked more at target objects than distractor objects following action primes. Such anticipatory eye movements were not visible after meaningless primes. After target name onset until target visual identification, eye movements towards semantically related and unrelated distractors were influenced by type of semantic display, type of prime and action prime encoding level. Action primes had the opposite effect on visual competition with thematically-related distractors (e.g. wood) depending on the encoding representational level, while action prime encoding did not affect competition with distractors that shared a specific (e.g. axe) or general (e.g. knife) function with the target (e.g., saw). Specifically, thematic competition was greater and earlier after action primes encoded at the gesture-level compared to higher-level of action representation. No effect of semantic display or encoding was observed on gaze competition for meaningless primes.

Results first showed that point-light displays of object-related actions primed object identification. This was visible in both the amount of anticipatory fixations on target objects right after the presentation of the point-light displays, and in target identification mouse response times. Many studies have reported effects of action priming on manipulable artifact conceptual processing (Borghi et al., 2005; Mounoud, Duscherer, Moy, & Perraudin, 2007) based on reaction time responses. The present experiment further highlights a strong influence of prior action activation on implicit oculomotor behavior during object visual exploration. Importantly, the action priming effects observed before target noun onset ensure that the impoverished point-light display stimuli were correctly perceived. Thus, the pattern of results to be discussed may not be attributed to potential difficulties in identifying the actions performed by the actor in the point-light display movies.

Second, we did not observe any overall competition effect – as well as any competition differences between semantic displays- after meaningless primes. Yet following previous eye-tracking studies comparing thematic, specific function, and general function competition in the absence of priming (Kalénine et al., 2012; Pluciennicka et al., submitted), one may have expected competition effects of similar amplitude but different temporal dynamics in the three semantic displays when the primes did not convey any information (random moving dots). Although designed as neutral as possible, meaningless primes seem to have actually worked as unrelated, inhibitory primes that cancel competition effects with semantically-related distractors. It is as if meaningless primes had the effect of a forward mask on semantic property activation from visual objects. This is interesting to consider, given the potential multimodal nature of semantic competition effects in the Visual World Paradigm. Semantic activation may be driven by processing of both linguistic input and visual objects. We know that eye movements can be directed by linguistic processing in the absence of current visual stimulus (Altmann, 2004, 2011), which highlights the importance of the linguistic locus of competition effects. The impact of visual display masking on semantic competition effects suggests that they may also have an important visual locus.

Finally, point-light displays action prime encoding was found to be critical for thematic competition effects during object identification. As predicted, action primes encoded at the gesture level ("sawing") tended to facilitate thematic knowledge implicit activation (saw-wood), whereas action primes encoded at the intention level ("cutting") tended to interfere with such activation. Since action primes that had not correctly associated to high-level action representations in the high-level encoding group were excluded from the analysis, we can ensure that the interference effect observed on thematic processing in this group was due to prior activation of high-level action representations. In the gesture-level encoding group, however, associations between action primes and gesture representations could not be explicitly verified. In this group, action priming had the reverse effect on thematic processing (i.e. facilitation), indicating that action primes had not been implicitly encoded at the intention level. Moreover, action primes induced anticipatory fixations on the corresponding objects before hearing the target name, confirming that participants recognized the gesture presented in the point-light display. Thus, we can be fairly confident that the opposite pattern of action priming effects on thematic processing are related to the level of action priming encoding, gesture-level versus intention-level.

This result directly demonstrates the influence of action representations on thematic processing, and the close relation between thematic knowledge and gesture-level action representations. In Kalénine et al. (2012)'s study, action representations conveyed by verbal primes had no impact on thematic relation implicit processing. Action representation influence was shown here with gesture primes, which reinforces the idea that gestures and thematic relations are highly connected. Moreover, putting the present finding in the perspective of previous results, it seems unlikely that the interference caused by high-level encoding of actions on thematic activation is related to the fact that action intentions were associated to point-light displays through language in the encoding phase. Thus, we believe that implicit processing of thematic relations relies, at least to a certain extent, on gesture-level action presentations.

The selective overlap between thematic relations and gesture-level action representations is consistent with growing evidence indicating that evocation of motor representations from visual objects is influenced by the action context (see van Elk et al., 2014 for review). Context and action intentions modulate the components of object multimodal representations that will be activated during object processing. In contrast to functionally similar objects that do not typically participate in the same action event, the presence of thematically-related objects provides a relevant action context for activation of object-related gestures. Activation of object-related gestures, enhanced by congruent action primes represented at the gesture-level, may in turn orient attention toward thematically-related objects that would be directly involved in target object use. Past studies have shown that explicit identification of thematic relations is facilitated when objects take part in the same action event, as compared to when objects are simply contextually related (Borghi et al., 2012; Tsagkaridis et al., 2014), and that this effect is enhanced when objects are positioned in a relevant way for action or when an agent is holding the tool (Yoon et al., 2010). The present study goes further and demonstrates that the connection between thematic and action knowledge is situated at the level of gesture representations involved during object use. Moreover, it shows that the interactions between semantic relations based on thematic knowledge and object-related gestures can affect object processing in an implicit manner, as witnessed here in participants' oculomotor behavior during object visual search.

The relationship between semantic relations based on functional similarity and action representations is less obvious. Point-light displays encoding did not affect implicit processing of specific function and general function similarity relations. One could have expected that high-level representations of action ("cutting") would facilitate general function similarity relation implicit processing (saw-knife) to a greater extent than gesture-level representations ("sawing"). However, this is not what we found. A possible explanation is that the association between point-light displays and high-level action representations following the encoding phase was not strong enough to impact general function competition. A challenge for future research is to develop experimental designs that allow inducing different levels of representation of an action while keeping the action stimulus constant. Another interpretation may be that if general function relations do not rely on gesture-level action representations, the gestural nature of the primes used in the present study is not well suited to general function knowledge activation, regardless of encoding. This would stress again the difference between functional similarity and thematic relations in terms of action representation involvement.

To conclude, the pattern of semantic competition effects observed during manipulable object identification in our action priming paradigm support the general idea that various types of semantic relations between manipulable artifacts differently rely on action. Findings suggest that thematic and functional similarity relation processing recruits different levels of action representation, i.e, gesture-level versus higher intention level. The different effects of action priming on semantic processing of those relations were visible in the pattern of eye movements during target object identification among distractors, and could not be attributed to specific object categorization instructions.

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6. Compliance with ethical standards

The authors declare that they have no conflict of interest. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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Appendix: List of stimuli and their normative values

English translation of the fourteen critical items *(original French stimuli)* presented in the Thematic, Specific Function, and General Function conditions. The last columns describe the object-related gestures displayed (* bimanual gestures, [objects] were not displayed), and the high-level action representations provided during High-Level point-light display encoding.

Reference object*	Thematic related object	Specific Function related object	General Function related object	Visually similar distractor	Unrelated distractor	Description of the object-related gesture	High-level intention used in the High-Level Encoding group
bowl *bol*	cereals *céréales*	feeding bottle *biberon*	plate *assiette*	belt *ceinture*	deer *biche*	Bringing [bowl] to the mouth using two hands in clench posture*	someone eating c'est quelqu'un qui est en train de manger
cap *bonnet*	scarf *écharpe*	hat *chapeau*	coat *manteau*	trash can *poubelle*	stool *tabouret*	Bringing [cap] to the top head using two hands in clench posture*	someone protecting himself c'est quelqu'un qui est en train de se couvrir
color pencils *crayons de couleur*	paper *papier*	paint *peinture*	pen *stylo*	bus *bus*	washing machine *machine à laver*	Coloring back and forth horizontal movement using right hand pinching [pencil]	someone drawing c'est quelqu'un qui est en train de dessiner
cup *tasse*	spoon *cuillère*	coffee maker *cafetière*	glass *verre*	whistle *sifflet*	trousers *pantalon*	Bringing [cup] to the mouth using right hand in pinch posture	someone drinking c'est quelqu'un qui est en train de boire
faucet *robinet*	pipe *tuyau*	sponge *éponge*	bucket seau	microphone *micro*	tractor *tracteur*	Rotating movement of the right hand clenching [faucet knob]	someone cleaning sth c'est quelqu'un qui est en train de nettoyer quelque chose
fishing rod *canne à pêche*	fish *poisson*	net (fishing) *filet*	boat *bateau*	seesaw *balançoire*	pineapple *ananas*	Rotating movement of the right hand pinching [rod handle], left hand holding [rod]*	someone fishing c'est quelqu'un qui est en train de pêcher
frying pan *poêle*	butter *beurre*	sauce pan *casserole*	cake mold *moule*	violin *violon*	camera *appareil photo*	Horizontal back and forth movement of the right hand clenching [pan handle]	someone cooking c'est quelqu'un qui est en train de cuisiner
lamp *lampe*	table *table*	candle *bougie*	mirror *miroir*	bell *cloche*	flag *drapeau*	Reaching movement of the right hand then right hand pinching [lamp switch]	someone decorating sth c'est quelqu'un qui est en train de décorer quelque chose
necklace *collier*	bracelet *bracelet*	dress *robe*	heels talons	drum *tambour*	tent *tente*	Reaching movement behind the neck with the two hands pinching [necklace ends]*	someone trying to look pretty c'est quelqu'un qui cherche à se faire joli
saw *scie*	wood *bois*	axe *hache*	knife *couteau*	feather *plume*	piano *piano*	Horizontal sawing movement of the right arm with right hand clenching [saw]	someone cutting sth c'est quelqu'un qui est en train de couper quelque chose
screwdriver *tournevis*	screw *vis*	*drill* *perceuse*	nail *clou*	flute *flute*	kite *cerf-volant*	Rotating movement of the right arm and hand clenching [screwdriver handle], left hand holding [screw]*	someone attaching sth c'est quelqu'un qui est en train de fixer quelque chose
suitcase *valise*	caster *roulette*	backpack *sac à dos*	basket *panier*	battery *pile*	chair *chaise*	Walking while pulling [suitcase] with hand clenching [suitcase handle]	someone transporting c'est quelqu'un qui est en train de transporter quelque chose
tape *scotch*	sheet of paper *feuille*	glue *colle*	paintbrush *pinceau*	panties *culotte*	pacifier *tetine*	Pulling [tape] with right hand pinching [tape end], left hand holding [tape dispenser]*	someone sticking sth c'est quelqu'un qui est en train de coller quelque chose
toothpaste *dentifrice*	toothbrush *brosse à dents*	soap *savon*	bath *baignoire*	sofa *canapé*	bike *vélo*	Applying [toothpaste] using right hand clenching [toothpaste tube], left hand holding [toothbrush]*	someone washing sth c'est quelqu'un qui est en train de laver quelque chose

*****All selected items are commonly known by French children. Many of them are used in everyday life (e.g., bowl, cup, color pencils) or have common toy replicates (e.g., saw, screwdriver, drill, pipe, fishing rod). Some relations may be culture-specific (e.g. drink from a bowl).

Mean values and standard deviations of normative ratings and LSA measures for the thematic, specific function and general function related and unrelated object pairs.

Semantic relationship	Visual similarity ratings	Manipulation similarity ratings	LSA measure
Thematic	1.18 (0.81)	3.64 (0.82)	0.34 (0.21)
Specific Function	2.28 (1.17)	4.68 (0.70)	0.32 (0.12)
General Function	2.18 (0.81)	4.14 (1.19)	0.21 (0.09)
Unrelated similar	2.41 (1.11)	1.40(0.32)	0.01 (0.04)
Unrelated	1.21 (0.19)	1.29 (0.18)	0.03 (0.05)

Figure1

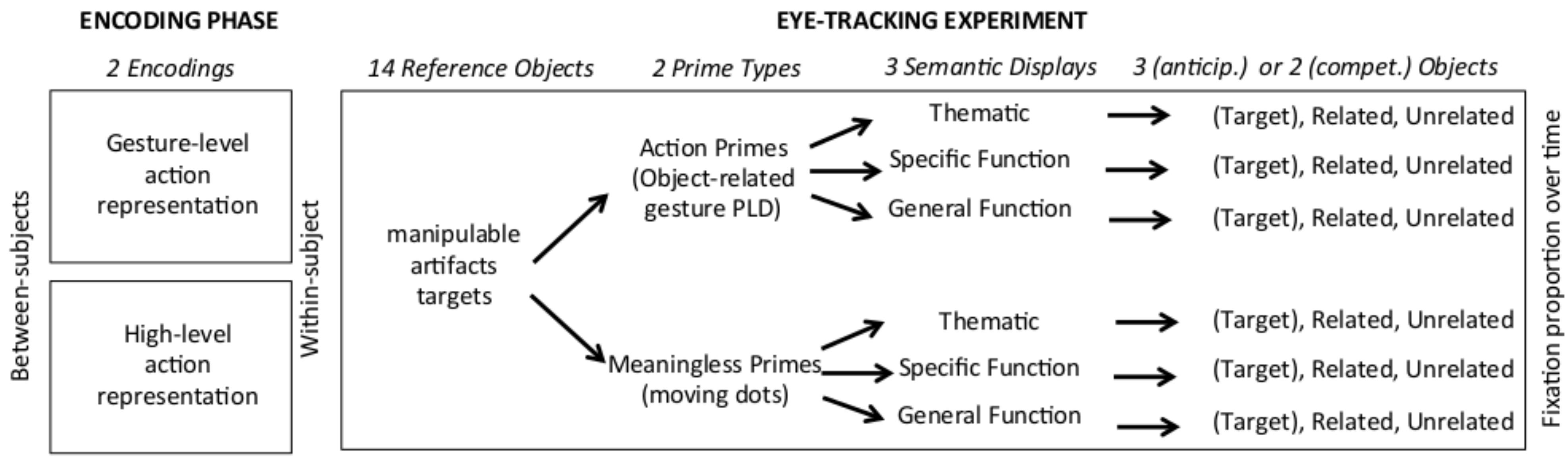

ENCODING PHASE
EYE-TRACKING EXPERIMENT
2 Encodings
14 Reference Objects
2 Prime Types
3 Semantic Displays
3 (anticip.) or 2 (compet.) Objects
Gesture-level action representation
High-level action representation
Between-subjects
Within-subject
manipulable artifacts targets
Action Primes (Object-related gesture PLD)
Meaningless Primes (moving dots)
Thematic
Specific Function
General Function
Thematic
Specific Function
General Function
(Target), Related, Unrelated
(Target), Related, Unrelated
(Target), Related, Unrelated
(Target), Related, Unrelated
(Target), Related, Unrelated
(Target), Related, Unrelated
Fixation proportion over time

Figure2

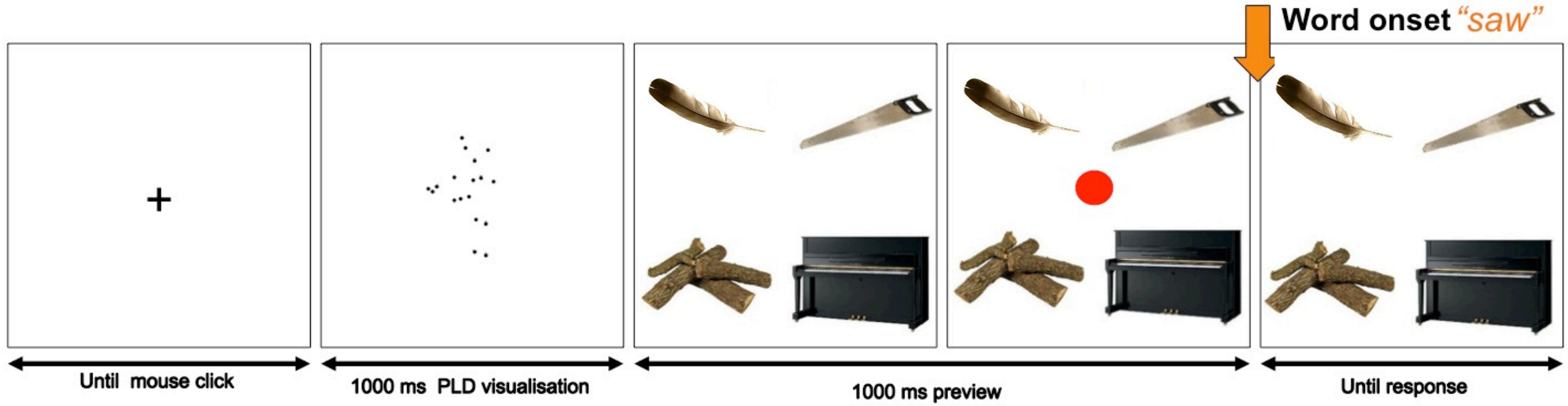

Word onset "saw"
Until mouse click
1000 ms PLD visualisation
1000 ms preview
Until response

Figure3

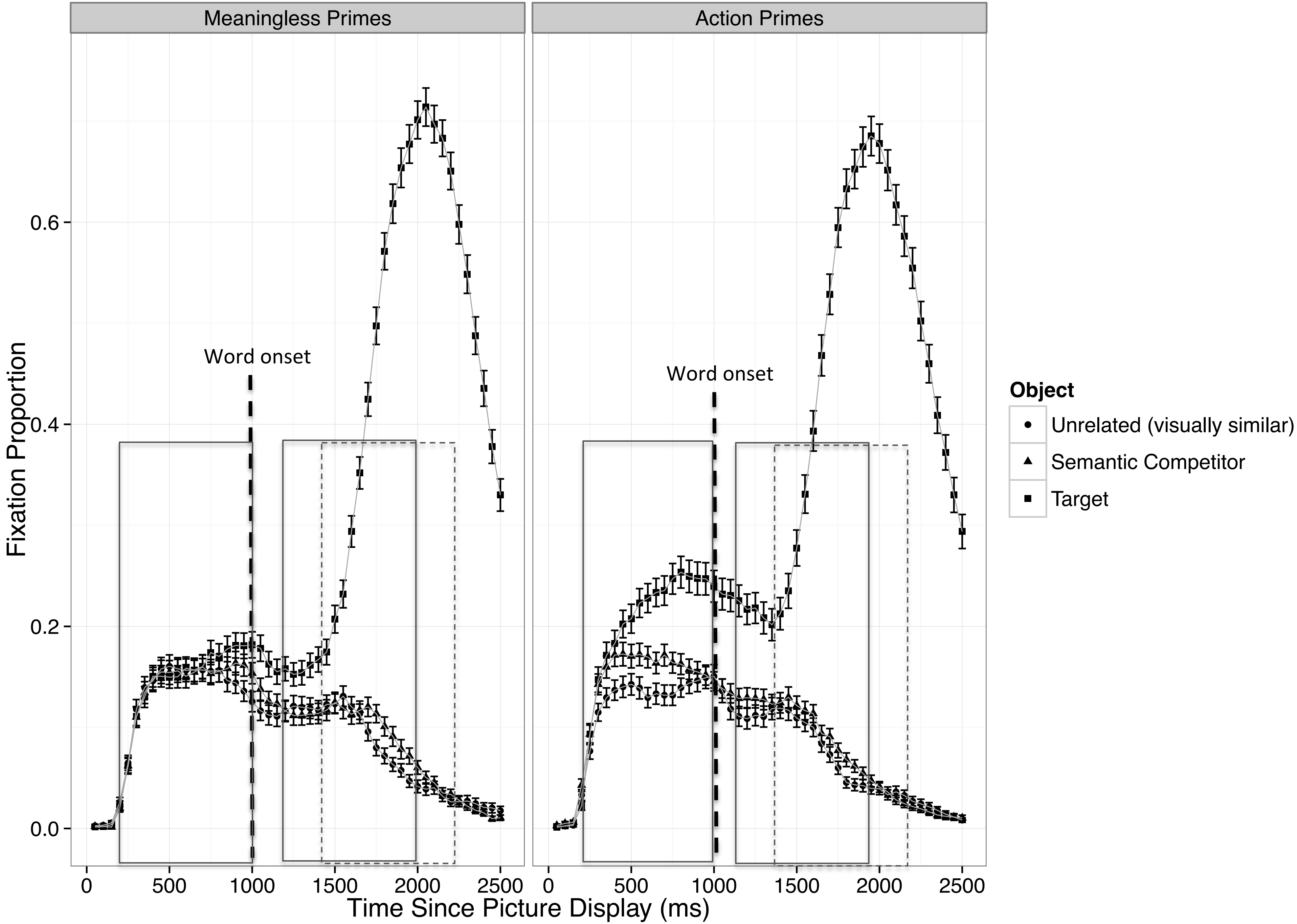
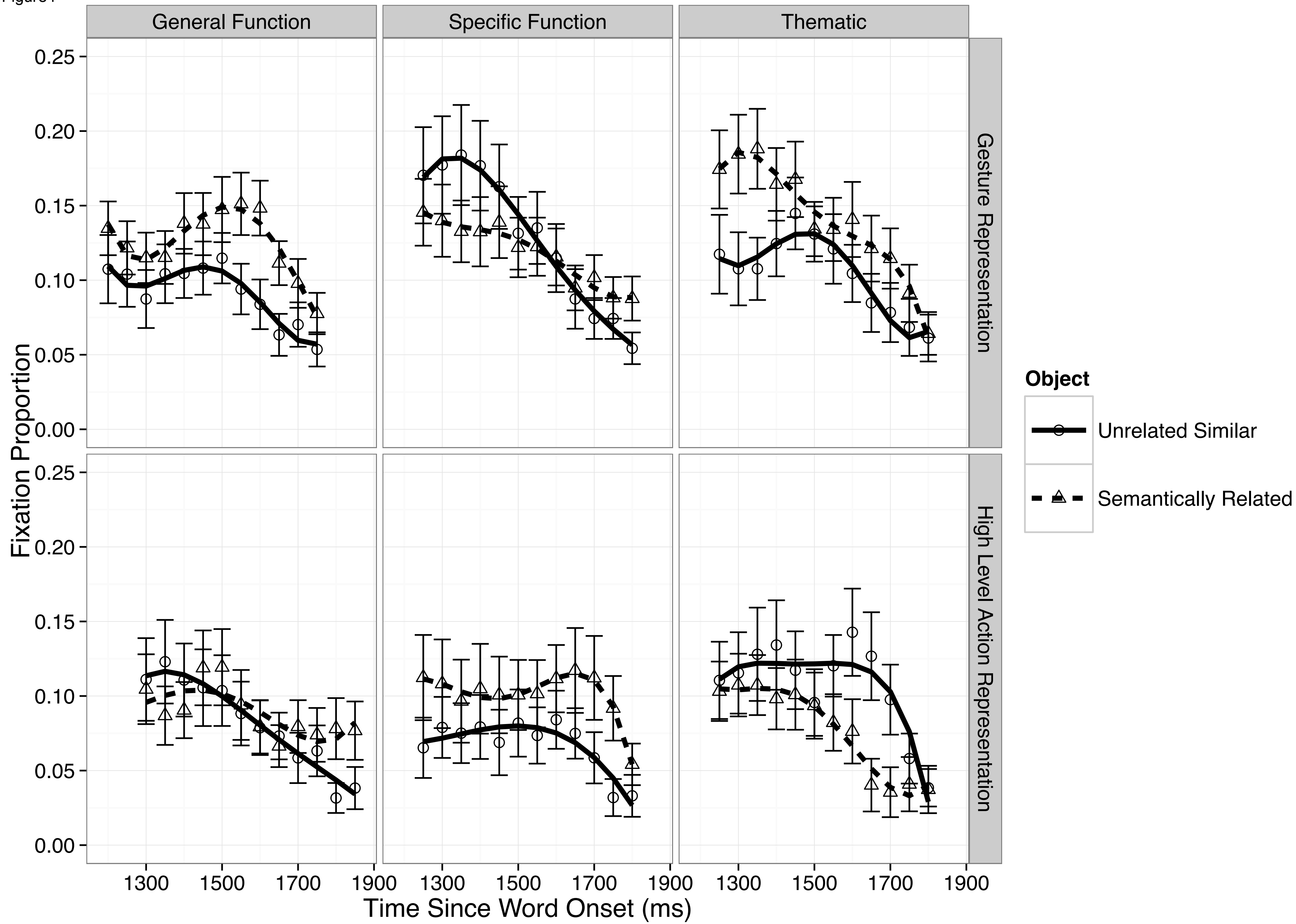

Meaningless Primes
Action Primes
Word onset
Word onset
Fixation Proportion
0.0
0.2
0.4
0.6
0
500
1000
1500
2000
2500
Time Since Picture Display (ms)
Object
Unrelated (visually similar)
Semantic Competitor
Target

Figure4


General Function
Specific Function
Thematic
Gesture Representation
High Level Action Representation
Fixation Proportion
0.00
0.05
0.10
0.15
0.20
0.25
1300
1500
1700
1900
Time Since Word Onset (ms)
Object
Unrelated Similar
Semantically Related