Abstract

Recent studies indicate that competition between conflicting action representations slows down planning of object-directed actions. The present study aims to assess whether similar conflict effects exist during manipulable object perception. Twenty-six young adults performed reach-to-grasp and semantic judgements on conflictual objects (with competing structural and functional gestures) and non-conflictual objects (with similar structural and functional gestures) presented at difference distances in a 3D virtual environment. Results highlight a space-dependent conflict between structural and functional affordances. Perceptual judgments on conflictual objects were slower than perceptual judgments on non-conflictual objects, but only when objects were presented within reach. Findings demonstrate that competition between structural and functional affordances during object perception induces a processing cost, and further show that object position in space can bias affordance competition.

Key words

Affordances; Action selection; Manipulable objects; Space; Virtual reality

Conflict between object structural and functional affordances in peripersonal space

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1. Introduction

Multiple action representations guide the execution of object-directed actions (Cooper & Shallice, 2006; Grafton & Hamilton, 2007; van Elk, van Schie, & Bekkering, 2014). In order to accomplish the desired outcome (e.g. drink), human agents need to select an object (e.g. cup), and derive the appropriate gesture (e.g., grasp handle). At each step, the cognitive system has to select the adequate action representation among several alternatives (Cisek, 2007). The resolution of the competition between several possible action candidates induces a processing cost and affects action execution. Consistent with this view, Jax and Buxbaum (2010, 2013) demonstrated that during action planning, structural and functional gesture representations associated to the same object interfere with one another. In healthy adults (Jax & Buxbaum, 2010), actions towards conflictual objects (with distinct structural and functional gestures, e.g., calculator) were more slowly initiated than actions towards non-conflictual objects (with similar structural and functional gestures, e.g., baseball). The cost observed for conflictual objects was even amplified in patients with ideomotor apraxia (Jax & Buxbaum, 2013), a deficit likely due to lesions of the supramarginal and inferior frontal gyri, two key regions for the resolution of action competition (Schubotz, Wurm, Wittmann, & von Cramon, 2014; Watson & Buxbaum, 2015). Together, recent studies indicate that conflict between action representations affects planning of object-directed actions. In contrast, the impact of competing action representations on object visual processing remains an open issue.

Important work has been done on the role of motor affordances in object perception. Although it is now clearly established that the perception of objects involves the retrieval of motor information through the activation of the visuomotor system (e.g., Chao & Martin, 2000; Ellis & Tucker, 2000), the content of the motor information evoked (i.e. the variety of affordances) has just started to receive some attention. Perceived objects reactivate many different action representations in a flexible way (Borghi & Riggio, 2015; Natraj, Pella, Borghi, & Wheaton, 2015; Thill, Caligiore, Borghi, Ziemke, & Baldassarre, 2013). In particular, perceived objects may evoke both structural and functional affordances (Bub, Masson, & Cree, 2008; Lee, Middleton, Mirman, Kalénine, & Buxbaum, 2013). Moreover, the relative importance of structural and functional gesture activation depends on visual context and action goals. For instance, Kalénine, Shapiro, Flumini, Borghi & Buxbaum (2014) showed that semantic categorization of conflictual objects entailed stimulus-response compatibility effects with the functional gesture when the object was presented in a use context (e.g. calculator on desktop), but with the structural gesture when the object was presented in a move context (e.g. calculator in drawer). Yet the existence of conflict effects between functional and structural affordances during object perception has never been demonstrated.

If, as growing evidence suggests, affordance evocation is flexible and context-dependent, then conflict effects between functional and structural affordances should be sensitive to the relevance of structural and functional gestures for the current situation. A critical determinant of gesture evocation may be object position in space. Space perception is not continuous and depends on individual motor capacities (Coello & Delevoye-Turrell, 2007; Costantini, Ambrosini, Sinigaglia, & Gallese, 2011). The perceived boundary of the action space delimitates individual peripersonal and extrapersonal spaces, where objects appear as reachable or not reachable, respectively. Critically, several studies have shown

that the evocation of motor affordances during object perception is maximum in peripersonal space (Costantini, Ambrosini, Scorolli, & Borghi, 2011; Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010; Ferri, Riggio, Gallese, & Costantini, 2011; Wamain, Gabrielli, & Coello, 2016; Yang & Beilock, 2011). In Costantini, Ambrosini, Scorolli, et al. (2011), participants had to judge the correctness of object-verb associations (e.g. bottle-pour). Objects could be presented in peri-and extra-personal spaces, and verbs could refer to structural actions, functional actions, or observation. An advantage for judgments involving action verbs compared to observation verbs was only observed when objects were presented in peripersonal space. This result indicates that structural and functional gestures are more (perhaps exclusively) activated when objects are presented in peripersonal space. Using immersive virtual reality technologies, Wamain et al. (2016) further showed that the greater activation of object motor affordances in peripersonal space was reflected at the neural level by an increased desynchronisation of Mu rhythm when objects were perceived as reachable. Notably, the neural modulation of affordance activation as a function of space was present when the perceptual task was relevant for action (i.e., reachability judgments), but not when the perceptual task focused on object surface properties (i.e. object versus non-object judgments). Together, research on action planning, object affordances and space perception suggests that the co-activation of structural and functional affordances during perception of conflictual objects may induce a processing cost. Nevertheless, such cost should be influenced by the position of the object in space and the relevance of the task for action. Perceptual judgments on conflictual objects should be slower than perceptual judgments on non-conflictual objects. The disadvantage of conflictual object processing should be greater in peripersonal space, and possibly more pronounced when the perceptual task orients attention towards the object properties that are relevant for action. These predictions were tested with the immersive virtual reality paradigm developed by Wamain et al. (2016).

2. Methods

2.1. Participants

Twenty-six young adults (mean age = 21; age range 19-26; 20 women) took part in the experiment. Data from one participant with response times greater than 3 standard deviations of the group mean were excluded from the analysis. The final sample included 25 participants. All were right-handed (handedness quotients 60–100%; mean 90%; Oldfield 1971), and had normal or corrected-to-normal visual acuity. The protocol was approved by the Ethical Committee of the University and was in accordance with the declaration of Helsinki. All participants gave written informed consent and were not paid for their participation.

2.2. Stimuli

Three-dimensional images of 40 unimanual manipulable objects were selected from open source 3D object databases and converted into OpenGL compatible format. Objects were displayed in virtual scenes generated with MatLab 6.5 (MathWorks, Natick, MA, USA) and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Among the 40 objects, 20 were conflictual (e.g. soap dispenser) and 20 were non conflictual (e.g. soda bottle, see Figure 1 bottom and Appendix A).

Conflictual and non-conflictual objects were selected from a pretest conducted on 9 right-handed participants who did not participate in the actual experiment. During pretest, 2D screen capture images of 3D objects were presented on a computer screen, and participants were asked to demonstrate how they would position their hand on the object in order to (1) move it and (2) use it (questions counterbalanced between participants). Hand postures were classified into 8 categories (open clench, closed clench, palm, pinch 2 fingers, pinch 3 fingers, poke, horizontal trigger, vertical trigger). Each object received a conflict index between 0 (highly conflictual) and 9 (highly non-conflictual) corresponding to the number of common hand postures provided between the move and use conditions. Conflictual and non-conflictual object categories had a mean index of 1.95 (SD = 1.85, range 0-5) and 7.8 (SD = 1.24, range 6-9), respectively. After hand posture production, participants were asked to tell in what room the object was typically found and to name it. Half of the final object set could be found in the kitchen.

Figure 1. Perception of conflictual (bottom left) and non-conflictual (bottom right) objects in the 3D virtual environment (top).

2.3. 3D immersive virtual reality system

Visual scenes were presented on a 2 m x 4 m rear projection screen using a 3D stereoscopic projector (Christie Mirage 4K35) generating images at 120 Hz with a 4 K spatial resolution (3840 x 2060 pixels). Active 3D eyewear (Christie) was used for producing 3D images perception. Images were generated taking into account participants' height. For each stimulus, two different images were computed and displayed 8.33 ms alternatively to each eye. Normal fusion created the illusion of viewing a single object. Relative size and perspective cues as well as binocular disparity were used to induce a 3D perception of the visual scene and objects. The visual scene was composed of a wooden textured table inside a rectangular room with wooden textured roof and tile-layered walls (Figure 1 top). Conflictual

and non-conflictual objects were presented on the virtual table at various distances according to the vantage point of the participant. Distances were individually normalized as a function of the perceived boundary of the peripersonal space of each participant. Objects were displayed at -50%, -60%, -70% (peripersonal space), -10%, 0%, +10% (boundary), +50%, +60%, +70% (extrapersonal space) of this boundary.

2.4. Procedure

Participants were equipped with Active 3D eyewear and seated approximately 100 cm from the screen. Eye-floor distance and right arm length were measured. Participants were asked to respond to the different judgments on the stimuli with their left and right feet using a pedal response device. Reach-and-grasp and semantic judgments were performed in two separate blocks counterbalanced between subjects¹. Prior to the two tasks, the boundary of peripersonal space was evaluated for each participant, and object stimuli were briefly presented for familiarization.

Determination of individual peripersonal space

A 7 cm x 7.5 cm cylinder was presented in the virtual environment at different distances from the participant. Distances varied randomly between 20 cm and 160 cm by steps of 5 cm. Each of the 29 distances was repeated 4 times. On each of the 116 trials, participants had to judge whether the cylinder could be reached and grasped with the right hand without performing the actual movement, using the pedal device. Yes/no response mapping onto left/right pedals was counterbalanced between participants. The stimulus remained visible on the screen until participants' response. The boundary of peripersonal space was determined using a maximum likelihood fit procedure based on second-order derivatives (quasi-newton method) to obtain the logit regression model that best fitted the reachable / unreachable responses of the participants (Appendix B). Individual boundaries of peripersonal space were used to compute the nine distances of presentation in the experimental tasks.

Object familiarization

2D screen captures of the 40 objects were presented and named one by one to ensure the correct recognition of all the objects used in the experimental tasks.

Reach-and-grasp and semantic judgment tasks

For each task, each of the 40 objects was presented at nine distances in the virtual environment (three per space). In the reach-and-grasp task, participants had to determine whether the object could be reached and grasped with the right hand without performing the actual movement. In the semantic task, they were asked to determine whether the object was typically found in the kitchen. The same response mapping as in the determination of individual space boundary was used. Objects appeared on the screen until participants' response. Inter-stimuli intervals randomly varied between 1500 and 1900 ms. There were 40 objects x 9 distances = 360 trials in each task presented in random order.

¹ We verified the presence of effects related to task order on reaction times and there were none, neither in isolation nor in interaction with other factors of interest.

3. Results

3.1. Perception of the reachability boundary

On average, participants perceived the cylinder as reachable when positioned at a maximum distance of 81 cm (SD = 23 cm), which corresponds to an overestimation of about 10% of their actual capacities (mean arm length = 72 cm, SD = 3 cm).

3.2. Perceptual processing of conflictual and non-conflictual objects in space

As correct responses were subjective in some experimental conditions (e.g., reach-and-grasp judgments at peripersonal space boundary), accuracy was not considered in the analysis. Response times (RTs) inferior to 200 ms and superior to 3000 ms were excluded (0.2% of trials). Mean RTs and standard deviations in the different conditions are reported in Table 1.

Table 1: Mean RTs in milliseconds (SD) as a function of Task (Reach-and-grasp, Semantic), Space (Peripersonal, Boundary, Extrapersonal), and Object (C = conflictual, NC = non-conflictual).

Reach-and-grasp						Semantic					
Peripersonal		Boundary		Extrapersonal		Peripersonal		Boundary		Extrapersonal	
C	NC	C	NC	C	NC	C	NC	C	NC	C	NC
820	802	945	970	832	852	886	848	876	852	875	858
(151)	(151)	(180)	(183)	(142)	(146)	(107)	(100)	(104)	(104)	(104)	(108)

Mixed-effect models were used to analyze RTs as a function of Space, Object, and Task (see Appendix C). There was a main effect of Space [$\chi^2(2) = 24.44$, $R^2 = .001^2$, $p = .001$]. RTs at the boundary of peripersonal space were 65 ms longer than RTs in peri- and extra-personal spaces [estimate = 64.36, $t = 6.22$, $SE = 10.62$, $p = .001$], which did not differ from each other [estimate = -15.47, $t = -1.01$, $SE = 15.38$, $p = .31$]. Space interacted with Task [$\chi^2(2) = 253.53$, $R^2 = .014$, $p = .001$], indicating that the effect of Space on RTs was present during reach-and-grasp judgments [$\chi^2(2) = 27.56$, $R^2 = .003$, $p = .001$] but not during semantic judgments [$\chi^2(2) = 0.15$, $R^2 = .017^{03}$, $p = .926$]. Critically, the expected Space x Object interaction was statistically significant [$\chi^2(2) = 7.29$, $R^2 = .004^{01}$, $p = .026$]. As illustrated on Figure 2A, the interaction was due to a 28 ms cost for conflictual objects compared to non-conflictual objects that was only present in peripersonal space [estimate = 27.91, $t = 2.11$, $SE = 13.24$, $p = .035$]. There was also an interaction between Task and Object [$\chi^2(1) = 3.77$, $R^2 = .002^{01}$, $p = .052$], reflecting an overall greater difference between conflictual and non-conflictual objects in the semantic than reach-to-grasp task (Figure 2B). However, the 3-way interaction between Space, Object, and Task was not significant [$\chi^2(2) = 2.07$, $R^2 = .001^{01}$, $p = .354$].

² Note that the interpretation of pseudo R^2 effect sizes in the case of linear mixed-effects models is not comparable to that of traditional linear models.

Figure 2. Mean conflict cost (mean of individual differences in RTs between conflictual and non-conflictual objects) as a function of A) Space, and B) Task. Error bars represent 95% confidence intervals. The $y = 0$ line corresponds to an absence of RT difference between conflictual and non-conflictual objects.

3.3. Complementary analysis

Using an index of object size in pixels, we verified that RTs in peripersonal space were predicted by object conflict index, but not object size index (see Appendix D).

4. Discussion

The present study demonstrated a space-dependent conflict between structural and functional affordances during the perception of manipulable objects in a virtual environment. Perceptual judgments on conflictual objects that are associated with distinct structural and functional gestures (e.g., soap dispenser) were slower than perceptual judgments on non-conflictual objects that are associated with similar structural and functional gestures (e.g., soda bottle), but only when objects were presented in peripersonal space.

The perceptual cost exhibited by conflictual objects can be attributed to the extent to which the structural and functional gestures associated to those objects are dissimilar,

rather to general differences between conflictual and non-conflictual object categories. The interaction between conflict effects and object position in space rules out any interpretation in terms of object familiarity or object name agreement, factors that have been considered in previous studies contrasting conflictual and non-conflictual objects (e.g., Watson & Buxbaum, 2015). Yet one may argue that physical differences between stimuli may be exacerbated with larger object images, which could have led to a selected processing cost for conflictual objects presented in peripersonal space. Using an index of object size on the screen based on low-level image characteristics, we ensured that physical differences between conflict and non-conflictual objects could not account for the pattern of results observed. Conflict index, but not object size index, predicted response times in peripersonal space. Thus, we can be fairly confident that conflict effects were due to the co-activation of distinct structural and functional gestures during object perception.

Conflict effects were not visible when objects were perceived out of reach. Unreachable objects may not evoke motor affordances at all, as previous EEG findings from Wamain et al. (2016) suggest, or unreachable objects may only evoke functional affordances, since the involvement of functional gestures in object visual representations may be more stable than that of structural gestures (Buxbaum & Kalénine, 2010; Lee et al., 2013). The present behavioral results cannot disentangle between the two alternatives. Future EEG studies should assess whether markers of motor recruitment during object perception (e.g. Mu rhythm modulation) show residual activation of functional gestures, dissociated from structural gestures, when objects are presented in extrapersonal space. Regardless, the present finding indicates the visual context in which objects appear is an important modulating factor of affordance evocation (Costantini et al., 2010; Kalénine et al., 2014), but also competition.

Object position in space and task demands influenced competition between structural and functional affordances independently in the present study. Previous studies have shown that the role of space on action evocation may be counteracted by other contextual and situational factors determining action relevance (e.g. ownership, Griffiths & Tipper, 2009, 2012). In accordance with such findings, task demands were expected to modulate the relationship between affordance evocation and space, with greater conflict effects in peripersonal space when the task was relevant for action (reachable or not) compared to when the task was irrelevant for action (can be found in the kitchen or not). However, conflict effect modulation as a function of space was observed irrespective of task. Although designed as less directly relevant for action, one possibility is that judging the object typical context of use remains somehow action-relevant. This interpretation is consistent with the unexpected greater conflict effects observed in the semantic task compared to the reach-and-grasp task, independently of space. Whereas structural gestures may be more relevant than functional gestures for reach-and-grasp judgments, both gesture types may be equally relevant for semantic judgments. Thus, little competition bias may have increased competition costs in the semantic task. The issue of the interactive effects of different contextual sources on competition between motor affordances is critical and should be addressed in future research.

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Appendix A : List of stimuli

Object	Category	Most frequent structural gesture	Most frequent functional gesture	Conflict index
Pan	Non Conflict	Closed clench	Closed clench	8
Pitcher	Non Conflict	Closed clench	Closed clench	6
Shower brush	Non Conflict	Closed clench	Closed clench	7
Wrench	Non Conflict	Closed clench	Closed clench	6
1L water bottle	Non Conflict	Open clench	Open clench	8
33cl can	Non Conflict	Open clench	Open clench	8
33cl soda bottle	Non Conflict	Open clench	Open clench	9
Baby bottle	Non Conflict	Open clench	Open clench	9
Baseball	Non Conflict	Open clench	Open clench	8
Beer bottle	Non Conflict	Open clench	Open clench	8
Minute glass	Non Conflict	Open clench	Open clench	9
Plastic cup	Non Conflict	Open clench	Open clench	8
Thermos mug	Non Conflict	Open clench	Open clench	9
Toilet detergent	Non Conflict	Open clench	Open clench	9
Vase	Non Conflict	Open clench	Open clench	8
Chopsticks	Non Conflict	Pinch	Pinch	7
Clothes pin	Non Conflict	Pinch	Pinch	6
House key	Non Conflict	Pinch	Pinch	9
Pan lid	Non Conflict	Pinch	Pinch	6
Pawn	Non Conflict	Pinch	Pinch	9
Scissors	Conflict	Closed clench	Horizontal trigger	0
Alarm clock	Conflict	Open clench	Palm	3
Calculator	Conflict	Open clench	Poke	2
Coffee cup	Conflict	Open clench	Pinch	1
Coffee grinder	Conflict	Open clench	Pinch	0
Computer mouse	Conflict	Open clench	Poke	1
Desk lamp	Conflict	Open clench	Poke	0
Detergent spray	Conflict	Open clench	Horizontal trigger	0
Flashlight	Conflict	Open clench	Poke	3
Hole punch	Conflict	Open clench	Open clench (other reponses= palm)	5
Paint spray	Conflict	Open clench	Vertical trigger	1
Parfume spray	Conflict	Open clench	Vertical trigger	4
Portable stove	Conflict	Open clench	Pinch	0
Remote	Conflict	Open clench	Poke	4
Soap dispenser	Conflict	Open clench	Palm	0
Speaker	Conflict	Open clench	Pinch	1
Spinning top	Conflict	Open clench	Pinch	4
Tape in dispenser	Conflict	Open clench	Pinch	1
Tea cup	Conflict	Open clench	Pinch	5
Dice	Conflict	Pinch	Pinch (other reponses = diverse)	4

Appendix B : Equation used to determined individual peripersonal space boundary

$$y = e(\alpha + \beta X) / (1 + e(\alpha + \beta X))$$

with:

y = participant's response

X = distance between

$(-\alpha / \beta)$ is the critical value of X corresponding to the transition between reachable and unreachable stimuli. Thus, $(-\alpha / \beta)$ expresses the perceived maximum reachable distance.

Appendix C : Data analysis using mixed-effect models

A mixed-effect model approach was used to analyze RTs as a function of Space (peripersonal, boundary of peripersonal, extrapersonal), Object (conflictual, non-conflictual), and Task (reach-and-grasp, semantic). Models included the full random effect structure with random intercepts and slopes for both participants and items. Augmented and reduced models (i.e. with and without the fixed effect of interest) were compared using -2LogLikelihood Ratio (distributed as χ^2 with degrees of freedom equal to the number of parameters added). Analyses were carried out with the *lme4 1.1-11* package of R version 3.2.4. Pseudo R^2 effect sizes were calculated using the *r.squaredLR* function of the *MuMin* package.

Appendix D : Complementary analysis

Object images may vary in their number of pixels (at a given distance). Although the processing cost entailed by conflictual objects was only visible in peripersonal space, this cost might be driven by physical differences between images categories of conflictual and non-conflictual objects that might be more salient when objects are presented at a close distance. Thus, we computed an index of object size in pixels in each space using the FSIM algorithm developed by Zhang, Zhang, Mou & Zhand (2011) to assess image similarity based on low-level visual features. With the FSIM algorithm, we compared the physical similarity between 2D screen captures of each conflictual and non-conflictual stimulus presented at 32 cm, 80 cm, and 130 cm (average distance for peripersonal, boundary of peripersonal, and extrapersonal spaces, respectively) and a 2D screen capture of the empty virtual scene. We then tested whether object conflict index (continuous measure evaluated during pretest) predicted RTs in peripersonal, boundary of peripersonal, and extrapersonal spaces, beyond object size index using regression models. In peripersonal space, object size index was not a significant predictor of RTs [$r = .24$, partial $R^2 = .06$, $p = .13$], whereas object conflict index was [$r = -0.40$, partial $R^2 = 0.16$, $p = .01$]. Moreover, neither object size nor object conflict indices predicted RTs at the boundary of peripersonal space and in extrapersonal space.