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How competition between action representations affects object perception during development

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Abstract

Recent evidence in adults indicates that object perceptual processing is affected by the competition between action representations. In the absence of specific motor plan, reachable objects associated with distinct structural (grasping) and functional (using) actions (e.g., calculator) elicit slower judgments than objects associated with similar actions (e.g., tennis ball). This effect is believed to reflect the cost entailed by the conflict between action representations. The present study aims to identify age-related changes in this conflict cost and investigate its underlying mechanisms. Five age groups from 8 to adulthood participated (n = 119). Participants performed perceptual judgments on different 3D objects in a virtual environment in order to assess their conflict cost (Experiment 1). Action priming effects and Simon effects were further assessed in the same participants as independent indices of the ability to activate action representations and to monitor conflict, respectively (Experiments 2 and 3). Experiment 1 demonstrated that the conflict cost is present in children as young as 8 and follows a non-linear, U-shape developmental trajectory between 8 and adulthood. Experiments 2 and 3 indicated that action priming effects showed a similar U-shape curve whereas Simon effects were stable across age groups. Action priming effects further predicted conflict costs at 10. Results suggest that the conflict cost relies on the ability to activate action representations from visual objects, which witnesses important changes during early adolescence. The role of general conflict monitoring abilities in conflict cost development requires further investigation. Findings will fuel models of action selection and embodied views of development.

Keywords: Action representations - Manipulable objects - Visual perception - Action priming - Child development- Embodied cognition

Introduction

There is now considerable evidence that motor representations associated with manipulable objects may be recruited during object visual processing in the absence of planning of object-direction actions (for review see Buxbaum & Kalénine, 2010; Thill, Caligiore, Borghi, Ziemke, & Baldassarre, 2013; van Elk, van Schie & Bekkering, 2014). Such evidence supports the existence of close interrelations between action, perception and object representations, in accordance with embodied views of cognition and development (e.g., Borghi & Cimatti, 2010; Matheson & Barsalou, 2018; Pexman, 2019; Smith, 2005a; Wilson, 2002). The essential role of sensorimotor experience for cognitive development is an old and well-acknowledged idea in developmental research (Laakso, 2011; Piaget, 1952), but some critical implications of embodied cognition theories for object processing have not been as deeply investigated in children. The incidental recruitment of specific components of object-related actions during object perceptual and semantic categorization is one of them. A few studies, however, showed that children as young as two activate and use motor representations when categorizing manipulable objects, even when action is irrelevant for the task (Smith, 2005b). Priming studies in school-aged children further demonstrated that the identification and categorization of manipulable objects are facilitated by prime stimuli conveying congruent action information from at least 7-8 years of age (Anelli, Borghi, Nicoletti, 2012; Collette, Bonnotte, Jacquemont, Kalénine, & Bartolo, 2016; Kalénine, Bonthoux, & Borghi, 2009; Liuzza, Setti, & Borghi, 2012; Mounoud, Duscherer, Moy, & Perraudin, 2007). However, despite convincing evidence that action representations may be recruited “off-line” during object visual processing in young children as well, the consequences of the activation of action representations on the development of object recognition and categorization remain largely unknown. The general aim of the present study was to shed light on the modifications in children's representation of visual objects that might be caused by developmental changes in action processing.

In adults, recent research has provided important refinements on the relations between action and object representations. First, the relation is not as automatic as previously thought. The activation of action representations during object perception may be modulated by several contextual factors, including task demands (e.g., Tipper, Paul, & Hayes, 2006; Wamain, Gabrielli, & Coello, 2016), visual context (e.g., Kalénine, Shapiro, Flumini, Borghi, & Buxbaum, 2014; Wokke, Knot, Fouad, & Richard Ridderinkhof, 2016), and location of the object in space (e.g., Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010; Ferri, Riggio, Gallese, & Costantini, 2011; Kalénine, Wamain, Decroix, & Coello, 2016; Wamain et al., 2016). Second, it is not obvious which action representations are actually activated and when. A single object may evoke different action representations in relation with different types of interactions that one may have with it (Bub, Masson, & van Mook, 2018; Kalénine et al., 2016; Wamain, Sahaï, Decroix, Coello, & Kalénine, 2018). In particular, visual objects may activate both structural and functional action representations (Buxbaum & Kalénine, 2010) that are associated with object grasping and using, respectively.

A few studies have directly investigated the impact of the co-activation of different structural and functional action representations on action planning (Jax & Buxbaum, 2010, 2013) and object perceptual processing (Kalénine et al., 2016; Wamain et al., 2018) in adults. In these studies, the authors compared the processing of "conflictual" and "non-conflictual" objects. Conflictual objects are associated with distinct structural and functional action representations (e.g., a calculator associated with clench and poke) whereas non-conflictual objects are associated with similar structural and functional action representations (e.g., a tennis ball only associated with clench). They highlighted a selective action production cost (Jax & Buxbaum, 2010, 2013) and a selective perceptual cost (Kalénine et al., 2016; Wamain et al.,

2018) for conflictual objects. In Kalénine et al. (2016), participants made perceptual judgments on conflictual and non-conflictual objects presented at different distances in a 3D virtual environment. Longer response times were observed for conflictual compared to non-conflictual objects, but this effect was only evidenced when objects were presented within reach. This finding demonstrates that the activation of multiple action representations induces a perceptual processing cost that depends on the possibilities of the observer to interact with objects. Together, these results suggest that when adults activate different structural and functional action representations associated to a single object, the different representations compete with one another and this competition is detrimental to object perceptual processing. Then one critical question is how the competition between action representations may change with age and affect the processing of visual objects throughout development. This was the goal of the first experiment of the present study.

Following neurobiological proposals in the domain of action selection (e.g., Cisek, 2007; Schubotz, Wurm, Wittmann, & von Cramon, 2014; Watson & Buxbaum, 2015), we hypothesized that the processing cost reported during the perception of manipulable objects results from the joint contribution of two mechanisms corresponding to the activation and monitoring of action representations. The perception of conflictual objects (e.g., calculator) within reach entails a strong co-activation of structural and functional action representations (activation) and, as the two action representations differ (e.g., clench and poke), a competition-for-selection occurs (monitoring). In two additional experiments conducted in the same participants, we evaluated action activation abilities and conflict monitoring abilities separately. The objective was to determine whether the development of the processing cost resulting from the implicit activation of conflicting action representations (first experiment) would parallel the development of these more basic action-related abilities.

In non-conflicting situations, there is evidence supporting the involvement of action representations in children's identification and categorization of visual objects from at least 7-8 years of age. Yet it seems that action representations are not activated in a homogeneous manner between early school age and adulthood. In particular, the facilitative effect of action priming on object categorization has been sometimes shown to disappear or even turn into an interference effect between 8 and adulthood (Collette et al., 2016; Kalénine et al., 2009; Mounoud et al., 2007). Regarding the monitoring of action representations, there is to our knowledge no data directly speaking to how it may develop. Nonetheless, the maturation of more general conflict monitoring abilities has been largely documented (see for example Hämmerer, Müller, & Li, 2014 for review), especially via the study of spatial congruency effects obtained with different versions of the Simon paradigm (Davidson, Amso, Anderson, & Diamond, 2006; Erb & Marcovitch, 2019; Hämmerer, Müller, & Li, 2014). Overall, results show that general monitoring abilities may be efficient by 10, but that they continue to develop during adolescence. Taken altogether, developmental studies indicate that from the beginning of elementary school, children activate action representations when identifying or categorizing visual objects. However, whether the involvement of action representations in object processing changes between elementary school and adulthood is less clear-cut. Moreover, indirect evidence suggests a progressive improvement of the ability to monitor action representations from 8-year-olds to adulthood, with processing in adolescents probably not reaching adult-level. Thus, action activation and conflict monitoring basic abilities may show different developmental trajectories. If both processes contribute to the competition between multiple action representations during object perception, then a non-linear development of the resulting processing cost may be anticipated, with periods when children easily activate action representations but poorly monitor them showing the maximum cost.

To sum up, the main goal of the present study was to specify the development of the object processing cost entailed by the perception of conflicting action representations during childhood. This is important to better understand how perception-action-cognition relations develop and their consequences for the representation of everyday objects. Furthermore, we wanted to determine whether the developmental trajectory of the conflict cost would follow age-related changes in action activation and conflict monitoring abilities, two basic processes that may be at play in the emergence of the conflict cost. As an important cost should be observed when action representations are easily activated but poorly monitored, we anticipated that the conflict cost may follow a non-linear development, with specific age periods at which children's ability to activate and monitor action representations might be beneficial but also detrimental to the processing of object properties.

We recruited five groups of participants from 8-year-olds to young adults. In the first experiment, they performed perceptual judgments on 3D stereoscopic images of objects displayed in a virtual environment using 3D active glasses (paradigm from Kalénine et al., 2016) in order to assess the developmental trajectory of the conflict cost. The same participants were further involved in two additional experiments that aimed at assessing their ability to activate and monitor action representations independently. The objective was to evaluate to what extent development of these abilities may contribute to age-related changes in the conflict cost. We chose two classical paradigms to evaluate the activation of action representations from objects and conflict monitoring abilities independently: the action priming paradigm (as in Borghi et al., 2007) and the Simon paradigm (as in Hommel, 2011). Experiment 1 was always conducted first. Then the order of the two additional experiments was counterbalanced between participants. Note that the same response mapping (yes/no responses to left/right keys) was used for a given participant between all experiments, but response mapping was counterbalanced across participants. All experiments were conducted within a single session of about an hour.

Experiment 1: 3D object perception of conflictual and non-conflictual objects

Participants

One hundred and sixty-one volunteers took part in the experiment. Left-handed participants were excluded as well as participants with reported neurological history. Data from two additional participants were not considered due to technical reasons. The sample then included 131 participants. They were divided into five age groups: 8- to 9-year-olds (3rd grade, n = 28, M = 8y 7m; SD = 4 m; 9 females); 10- to 11-year-olds (4th grade, n = 25, M = 10y 10 m; SD = 5 m; 14 females); 12- to 13-year-olds (5th grade, n = 23, M = 12y 11m; SD = 6 m; 12 females); 14- to 15-year-olds (6th grade, n = 21, M = 14y 7m; SD = 4 m; 10 females); and young adults (n = 34, M = 20y 7m; SD = 2y 10m; 31 females). All were right-handed, confirmed by the school teacher for the two younger groups (8- to 9- and 10- to 11-year-old children), or assessed by handedness questionnaire (Oldfield, 1971) for the three older groups (12- to 13-year-olds: 0.80, 14- to 15-year-olds: 0.81; young adults: 0.77). All participants had normal or corrected-to-normal visual acuity. Children were recruited in two elementary schools and one middle school. Young adults were undergraduate students of Lille University. Participants provided written informed consent and were not paid for their participation. Parents of minor participants gave authorization for their children to participate in the study. The protocol was approved by the Ethical Committee of the University of Lille and was in accordance with the declaration of Helsinki. Participants were explicitly asked to tell the experimenter to stop the experiment in case of important discomfort or sickness with the virtual reality system.

Methods

Materials and procedure

The main experiment aimed at assessing the processing cost entailed by the competition between conflicting action representations when participants performed perceptual judgments on manipulable objects. The virtual reality protocol used was adapted from Kalénine et al. (2016) and Wamain et al. (2018).

Stimuli. Stimuli were three-dimensional images of 40 common manipulable objects created with Blender software. Half usually involved distinct hand postures for move and use actions (e.g., calculator) and were considered "conflictual" objects, and half usually involved similar hand postures for move and use actions and were considered "non-conflictual" objects (e.g., drinking glass, Figure 1 and Supplementary materials). In each category, half were kitchen objects and half were non-kitchen objects. Objects were displayed on a wooden table in a virtual scene (Figure 1) at different distances from the participant. Nine distances were sampled for each age group according to the average arm length at this age from -55% to 55% of the arm length. The nine distances were separated in near (-55%, -50% and -45%), limit (-5%, mean arm length, +5%) and far (+45%, +50% and +55%) spaces. This procedure ensured that regardless of the group and the individual perceived reaching boundary computed offline (see Result section), most participants would see objects both within reach and out of reach. Images were generated prior to the experiment by taking into account the distance to the screen (40 cm) and the mean arm length for each age group (see exact distances in Supplementary Table).

As conflictual and non-conflictual objects may differ in terms of visual complexity, an objective measure of visual complexity was obtained for each object image using the FSIM algorithm (Zhang, Zhang, Mou, & Zhang, 2011). FSIM provides a sensitive index of low-level visual similarity between two images. Each object image (object + scene) was compared to the image of the empty scene (scene only) and the resulting similarity index was used as index of visual complexity of the object image in the data analysis of this experiment.

Procedure. Participants were seated in front of an LCD screen (1920 x 1080 pixels, 120 Hz) with their hands resting on the armrest of the chair. A pedal response device was positioned under their feet. Stimuli presentation was controlled by custom software using MATLAB 9.2 (MathWorks, Natiek, MA, USA) and Psychophysics Toolbox extensions (Brainard, 1997). Active 3D eyewear (NVIDIA 3D vision 2, P1431) was used for producing 3D image perception. Two different images of each stimulus were computed and presented 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.

Before the starting of the experimental session, the 40 selected objects were presented and named one by one to ensure correct identification by each participant. The experimental session was composed of two judgement tasks completed in separate blocks, block order being counterbalanced between participants. In the reach-to-grasp judgment task, participants had to judge whether they could reach and grasp the object with their right hand without moving their arms or hands. In the semantic judgment task, they were asked to judge whether the object could be found in the kitchen or not. In both tasks, the object appeared at a given distance and remained displayed on the screen until participant's response. Inter-stimuli intervals were composed of a blurred virtual environment without object, and randomly varied between 1500 and 1900 ms. The object remained displayed until the participant's response. There were 360 experimental trials (40 objects x 9 distances) randomly presented in each block, preceded by 20 practice trials.

[Figure 1 about here]

Data analysis

Following Kalénine et al. (2016) and Wamain et al. (2018), the conflict cost was tested via the interaction between the type of object (conflictual vs. non-conflictual) and space (reachable, non -reachable). This interaction reflects the variation between response times for conflictual versus non-conflictual objects presented within reach (where they are assumed to activate both structural and functional action representations) in comparison to response times for conflictual versus non-conflictual objects presented out of reach (no activation of action representations). The individual perceived reachability boundary was determined a posteriori on the basis of individual responses in the reaching task ("Yes, it is reachable" vs. "No, it is not"). A maximum likelihood fitting procedure was used to obtain the logit regression model that best fit the reachable/unreachable responses of the participant with respect to the distance. The individual perceived reachability boundary corresponds to a fifty percent chance for the participant to say "yes, it is reachable". Then the different distances were divided into reachable and unreachable spaces at the individual level according to the perceived boundary of the peripersonal space of each participant. Two separate reachable and unreachable spaces could not be identified in 12 out of 131 participants (4 in 8-year-olds, 6 in 10-year-olds, 1 in 12-year-olds, 1 in young adults), who were excluded from further analyses. The final sample included 119 participants: 24 in the 8-year-old group, 19 in the 10-year-old group, 22 in the 12-year-old group, 21 in the 10-year-old group and 33 in the young adult group. Overall, the mean perceived reachability boundary in the present virtual environment was of 96 cm with no significant effect of age [F(4,114) = 1.96, p = . 10]: 89 cm (SD = 19 cm) in 8-year-olds, 99 cm (SD = 17 cm) in 10-year-olds, 93 cm (SD = 22 cm) in 12-year-olds, 102 cm (SD = 18 cm) in 14-year-olds and 100 cm (SD = 20 cm) in young adults (p-value for all Tukey post-hoc pairwise comparisons > .15).

The first goal of the study was to evaluate the general developmental trajectory of the conflict cost between action representations. To this aim we opted for the Bayesian statistical analysis framework. In comparison to null hypothesis significance testing, Bayesian analyses do not state on “significant” or “non-significant” results (Benjamin et al., 2018; McShane, Gal, Gelman, Robert, & Tackett, 2019) but report P(θ | data), the probability distribution of the model’s parameters (or quantities of interest derived from them) that are consistent with the model, observed data and prior information. Here, we summarize the uncertainty in our inference results by reporting the 95% credibility intervals (CI; 2.5%-97.5% quantiles) of the quantities of interest as well as the probability (P+) of the quantities of interest θ being greater than zero, P+ = P(θ > 0 | data). Closer the probability P+ to zero (0) or to one (1), stronger the weight accorded to negativity or positivity of the effect, i.e. the presence of a difference between conditions in one or the other direction.

Response times (RTs) were the dependent variable. We analyzed RTs with Bayesian generalized linear multilevel models using the 2.14.0 version of the “brms” package together with the Stan MCMC sampler version 2.24.1 (Bürkner, 2017; Carpenter, Gelman, Hoffman, Lee, Goodrich, et al., 2017) An ex-gaussian distribution of RT with a log link function was modeled to better capture the typical characteristics of RT distribution, i.e. skewness and non-decision time period. Importantly, as the difference of two log values may be expressed as a log ratio (log(A)-log(B)= log(A/B)), estimates of the model will correspond to log ratios. Log ratios of RTs can be easily translated in percentage of RT increase between conditions (log ratio = 0.05 corresponds to 5% increase).

The model involved several fixed and random effects. Fixed effects allow evaluating the effect of the factors of interest at the group-level and included Age group (8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults), Space (reachable, unreachable), Object type (conflictual, non-conflictual), Task (reachability, semantic) and their interactions. Visual complexity was also added as fixed effect in interaction with Age group, Space, and Task in order to take into account the potential confound between Object Type and Visual Complexity. Random effects allow adjusting group-level effects for each individual. The random effect structure was kept maximal (Barr, Levy, Scheepers, & Tily, 2013) and included random intercepts and random slopes for Space, Object Type, Visual Complexity, Task and their interactions. Developmental trajectories of the effects of interest (i.e. the conflict cost reflected by the Object Conflict x Space interaction, possibly modulated by Task) were evaluated using orthogonal polynomial contrasts. Orthogonal polynomial contrasts (n groups – 1) are very useful to describe the shape of a developmental curve (see also the literature on growth curve analysis, e.g., Curran, Obeidat, & Losardo, 2010; Mirman, 2014). As we were particularly interested in the linear versus non-linear developmental changes in the conflict cost, we focused on linear, quadratic, and cubic polynomial contrasts. The linear contrast tests whether the trajectory is regularly increasing or decreasing with age. Evidence for linear changes suggests *quantitative* changes in the processes evaluated. The quadratic contrast evaluates whether the trajectory is in a U or inverted-U shape and the cubic contrast captures additional irregular increases or decreases of performance with age. Evidence for quadratic and/or cubic non-linear changes rather suggests *qualitative* changes (e.g., shift, restructuration) in the processes evaluated.

Results

As responses were sensitive to participant's subjectivity in both experimental tasks, accuracy was not considered in the analysis. Response times (RTs) below 200 ms and exceeding 5 times the median by age group were excluded from the analysis. Then RTs were trimmed by removing those exceeding 3 standard deviations from the participant's mean in each condition. Overall, 2.8 %, 2.0 %, 2.3 %, 2.2 % and 2.0% of trials were excluded from the analyses for 8-

year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults, respectively. Mean RTs and standard deviations in the different conditions are reported in Table 1 and displayed on Figure 2.

[Table 1 about here]

[Figure 2 about here]

Irrespective of age, the Bayesian analysis of RTs showed strong evidence for an effect of Space (Est. of [log(Unreachable / Reachable)] = 0.086, 95% CI = [0.072; 0.100], P+ = 1), for an effect of Object Type (Est. of [log(Conflict/Non Conflict)] = 0.023, 95% CI = [0.017; 0.030], P+ = 1), and for an interaction between Object Type and Space (Est. of [log(Conflict/Non conflict| Reachable) – log(Conflict/Non conflict | Unreachable)] = 0.013, 95% CI = [0.003; 0.025], P+ = 0.99). The analysis further provided strong evidence for a modulation of the Object Type x Space interaction by Task (Est. for [difference in log(Conflict/Non conflict | Reachable) - log(Conflict/Non conflict | Unreachable) between Reachability and Semantic Tasks] = -0.033, 95% CI = [-0.054; -0.012], P+ = 0.99]. Overall, participants were 1.3% slower to judge conflictual objects than non-conflictual objects presented in their reachable space, as compared to their unreachable space, and this effect was stronger for reachability judgments than semantic judgments.

Regarding the effect of age on this pattern, the Bayesian analysis found strong evidence for a linear decrease of the effect of Space with age (Est. for [linear coefficient of log(Unreachable/Reachable)] = -0.065, 95% CI = [-0.092; -0.036], P+ = 0.00), but no clear evidence for age-related changes in the effect of Object Type in isolation. Critically, there was only weak evidence for *linear* changes in the interaction between Object Type and Space (Est. for [linear coefficient of log(Conflict/Non conflict | Reachable) – log(Conflict/Non conflict|

Unreachable)] = 0.004, 95% CI = [-0.019; 0.026], P+ = 0.62) or in the interaction between Object Type, Space and Task (Est. for [linear coefficient of the difference in log(Conflict/Non conflict | Reachable) – log(Conflict/Non conflict | Unreachable) between Reachability and Semantic Tasks] = 0.011, 95% CI = [-0.034; 0.056], P+ = 0.69). In contrast, the analysis showed moderate evidence for *quadratic* changes in the interaction between Object Type and Space (Est. for [quadratic coefficient of log(Conflict/Non conflict | Reachable) – log(Conflict/Non conflict | Unreachable)] = 0.021, 95% CI = [-0.003; 0.045], P+ = 0.96). The evidence that the quadratic trajectory of the Object Type x Space interaction was further modulated by Task was weak (Est. for [quadratic coefficient of the difference in log(Conflict/Non conflict| Reachable) – log(Conflict/Non conflict| Unreachable) between Reachability and Semantic Tasks] = 0.018, 95% CI = [-0.027; 0.064], P+ = 0.79). Finally, there was weak evidence for *cubic* changes in the interaction between Object Type and Space (Est. for [cubic coefficient of log(Conflict/Non conflict| Reachable) – log(Conflict/Non conflict | Unreachable)] = = -0.016, 95% CI = [-0.044 0.009], P+ = 0.11) or in the interaction between Object Type, Space and Task (Est. for [cubic coefficient of the difference in log(Conflict/Non conflict| Reachable) – log(Conflict/Non conflict| Unreachable) between Reachability and Semantic Tasks] = 0.016, 95% CI = [-0.034; 0.065], P+ = 0.74). There was strong evidence for an Object Type x Space interaction in 8-year-olds (Est. for [log(Conflict/Non conflict | Reachable) – (Conflict/Non conflict | Unreachable)] = 0.028 95% CI = [0.003; 0.054], P+ = 0.99) and in young adults (Est.= 0.023, 95% CI = [0.006; 0.040], P+ = 1.00) but weak evidence for such an interaction in the other age groups. The two extreme groups were about 2.5% slower to categorize conflictual objects than non-conflictual objects where objects were perceived as reachable, in comparison to when objects were perceived as unreachable. This pattern is highlighted in Figure 3. The different results of the model are also provided in Table 2.

[Figure 3 about here]

[Table 2 about here]

In brief, evidence for an interaction between Space, Object Type and Task on response times highlights slower processing for conflictual objects presented within reach, a relative cost even more pronounced when participants performed reachability judgements. Evidence for an interaction between Space, Object Type and Age on the quadratic contrast further indicates that this cost develops non-linearly with age in a U-shape manner. Test of the Space x Object Type interaction in each age group further specifies how the U-shape maps on the different age groups and highlights a disappearance of the cost between 10 and 14 years of age.

Interim discussion

As a whole, results corroborate previous findings (Kalenine et al., 2016) with a different virtual set up and a different set of stimuli. Participants were slower to categorize conflictual objects that are associated with distinct structural and functional actions than non-conflictual objects that are associated with similar structural and functional actions, but this difference was more important when objects were perceived within reach than unreachable. Although the influence of virtual reality on this pattern cannot be excluded, we can be confident that all participants perceived objects as differently positioned in space in the virtual environment, as separate reachable and non-reachable spaces were determined for each of them. In addition, we found strong evidence for a modulation of this effect as a function of the perceptual judgment task: the effect was stronger for reachability judgments, a task that is highly relevant for action, than for semantic judgments that are less directly relevant for action. This subtle additional modulation as a function of task demands was observed irrespective of age on the whole sample of 119 participants. Competition between structural and function action representations have been shown to slow down action initiation (Jax & Buxbaum, 2010). In the absence of object-directed action, there is now important behavioral and neurophysiological evidence that visual objects mostly activate action representations when they are perceived in the peripersonal space of the observer (Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010; Ferri, Riggio, Gallese, & Costantini, 2011; Wamain, Gabrielli, & Coello, 2016) and/or when the task is relevant for action (Tipper et al., 2006). Therefore, we believe that the specific processing cost associated with the processing of reachable conflictual objects reflects the cost of the competition between action representations. As conflictual objects may also be more visually complex, we strictly controlled this potential confounded factor in the statistical analysis. There was still important evidence for a selective cost for reachable conflictual objects after controlling for this factor. Therefore, we can be confident that the pattern of results observed may not be fully explained by low-level differences in visual complexity.

The main results highlight a non-linear, U-shape developmental trajectory of the difference between conflictual and non-conflictual objects as a function of space (i.e., the conflict cost) between 8 years of age and adulthood. While both 8-year-old children and young adults showed strong evidence for a processing cost when conflictual objects were perceived within reach, the cost completely disappeared from 10 and did not become evident again before adulthood. We hypothesized that two separate mechanisms might contribute to the selective cost entailed by the perception of reachable conflictual objects: *activation* and *monitoring* of action representations. Therefore, we wanted to assess the ability of the same participants to activate and monitor action representations independently and evaluate to what extent these abilities may be related to the age-related changes observed in the conflict cost. To this aim, we conducted two additional experiments assessing action priming effects (*activation*) and Simon effects (*monitoring*) in the same participants.

Experiment 2: Action priming

Participants

The same 119 participants took part in Experiment 2.

Methods

Materials and procedure

We used the same action paradigm as Godard et al. (2019) inspired by (Borghi et al., 2007). It evaluates to what extent visual object categorization is facilitated by the prior presentation of hand pictures displayed in a congruent grasping posture. Action priming effects are assumed to reflect the activation of action representations during object processing (independently from conflict and space contribution).

Stimuli. Fifty high resolution colored photographs of objects were selected from an open source database (Pixabay). Half were manufactured (e.g., bowl) and half were natural (e.g., apple). 2D object pictures were displayed in the middle of the screen in a fictive square of 500 x 500 pixels on a black background (see Supplementary materials). Forty were used as experimental trials and ten as practice trials. Half of the objects used were usually grasped with a precision grip (e.g. hazelnut, pen cap) while the other half were usually grasped with a power grip (e.g. apple, bowl) according to their typical size. In addition, colored photographs of five different hand postures of 1920 x 1080 pixels on a black background were designed. Among hand postures, two displayed a grasping hand posture (power or precision grip) and three displayed a non-grasping hand posture (palm-up, palm-down and fist).

Procedure. Stimuli were inserted in an action priming paradigm with hand pictures as primes and object pictures as targets. Each trial started with a central fixation cross presented for 500 ms on a black background followed by one of the hand primes for 500 ms. Then the object target was presented until participants' response or for a maximum of 4000 ms. Participants were asked to categorize the target object as natural or manufactured by pressing one of the two response buttons with their left and right hand. Response mapping was counterbalanced between participants.

During the experimental phase, each target object was presented twice, once with the appropriate grasping hand prime (power or precision grip) in the action priming condition and once with one of the two non-grasping hand primes (palm-down or fist) in the neutral priming condition, leading to 80 experimental trials. Eight additional catch-trials (10%) were designed using four additional target objects presented with the palm-up “no-go” prime. On catch-trials, participants were asked to refrain from responding in order to ensure that they paid attention to the primes during the procedure. Participants performed 88 trials (40 action priming conditions, 40 neutral priming conditions and 8 catch-trials) presented in random order and preceded by 20 practice trials involving six additional target objects (three of each category).

Data analysis

As in the main experiment, Bayesian generalized linear multilevel models with an ex-gaussian RT distribution and a log link function were used to evaluate the effects of the factors of interest on correct response times. Fixed effects included Age group (8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults), Priming (action, neutral), Object Category (natural, manufactured), Object usual grasp (clench, pinch) and their interactions. The main effect of Priming was the effect of interest but we also added object category and object usual grasp to the model, as these factors have been shown to influence categorization in previous action priming studies (Borghi et al., 2007; Godard et al., 2019). The structure of random effects was kept maximal and included random intercepts for participants and random slopes for Priming, Object Category, Object usual Grasp and their interactions.

Results

Catch-trials were not considered in the analysis of action priming data. In addition, response times for incorrect responses and RTs below 200 ms and RTs exceeding 5 times the median by age group were excluded from the analyses. Then RTs were trimmed by removing those exceeding 3 standard deviations from the participant's mean in each condition. Overall, 9.6 %, 6.6 %, 6.0 %, 5.3 % and 3.9 % of trials were excluded from the analyses for 8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults, respectively[1]. Mean RTs and standard deviations in the different conditions are reported in Table 3.

[Table 3 about here]

Irrespective of age, the Bayesian analysis of RTs showed strong evidence for an effect of Priming (Est. of [log (Neutral/Action)] = 0.019, 95% CI = [0.004; 0.034], P+ = 0.99). Categorization times were overall 1.9% faster when the objects were preceded by an action prime in comparison to a neutral prime. The analysis provided only weak evidence for a modulation of the effect of Priming by Object category (Est. of [log(Neutral/Action | Manufactured) – log(Neutral/Action | Natural)] = -0.004, 95% CI = [-0.031; 0.023], P+ = 0.38) but relatively strong evidence for a modulation of the effect of Priming by Object usual Grasp (Est. of [log(Neutral/Action | Pinch) – log(Neutral/Action | Clench)] = -0.025, 95% CI = [-0.051; 0.001], P+ = 0.03) with greater priming for clenchable objects than pinchable objects.

Regarding the effect of age on this pattern, the Bayesian analysis showed only weak evidence for *linear* changes in the Priming effect (Est. for [linear coefficient of log(Neutral/Action)] = -0.001, 95% CI = [-0.033; 0.027], P+ = 0.45) or in the interaction between Priming and Object usual Grasp (Est. for [linear coefficient of [log(Neutral/Action |

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[1] Note that because younger children made more errors, the proportion of trials removed declined with age. We thus verified that these variations did not affect the developmental pattern of results observed. Developmental trajectories remain the same. The supplementary analysis without error exclusion for the two additional experiments is provided on OSF (https://osf.io/cvsdu/?view_only=22cd00af678047a4aadaaf2f41a89bc7).

Pinch) – log(Neutral/Action | Clench)] = -0.007, 95% CI = [-0.062; 0.049], P+ = 0.41). However, there was moderate evidence for *quadratic* and *cubic* changes in the Priming effect (Est. for [quadratic coefficient of log(Neutral/Action) = 0.024, 95% CI = [-0.008; 0.056], P+ = 0.93; Est. for [cubic coefficient of log(Neutral/Action) = - 0.029, 95% CI = [-0.063; 0.004], P+ = 0.04). More specifically, there was strong evidence for a Priming effect in 8-year-olds (Est. of [log (Neutral/Action)] = 0.041, 95% CI = [0.005; 0.078], P+ = 0.99), in 14-year-olds (Est. of [log (Neutral/Action)] = 0.036, 95% CI = [0.007; 0.064], P+ = 0.99) and in young adults (Est. of [log (Neutral/Action)] = 0.020, 95% CI = [0.004; 0.037], P+ = 0.99), but weak evidence for a Priming effect in 10 and 12-year-olds (see Figure 4). Although not anticipated, the analysis also found strong evidence for *quadratic* and *cubic* changes in the interaction between Priming and Object usual Grasp (Est. for [quadratic coefficient of [log(Neutral/Action | Pinch) – log(Neutral/Action | Clench)] = 0.063, 95% CI = [0.004; 0.118], P+ = 0.98); Est. for [cubic coefficient of [log(Neutral/Action | Pinch) – log(Neutral/Action | Clench)] = -0.069, 95% CI = [-0.128; -0.010], P+ = 0.01). There was strong evidence that Object usual Grasp modulated Priming in 10-year-olds (Est. of [log(Neutral/Action | Pinch) – log(Neutral/Action | Clench)] = -0.100, 95% CI = [-0.170; -0.031], P+ = 0.00), but not in the other age groups.

[Figure 4 about here]

Interim discussion

Results from the action priming experiment corroborate the general action priming effect previously observed with the same paradigm (Godard et al., 2019): overall participants were around 20 ms faster (1.9% RT decrease) to categorize visual objects as natural or manufactured when objects were preceded by the picture of a hand in a congruent grasping posture. Yet there was no evidence for a greater impact of action primes on manufactured than natural objects, as reported in Godard et al. (2019). In addition, there was also strong evidence for greater action priming effects for clenchable than pinchable objects, a modulation that was not anticipated. The reasons for discrepancies between studies in the possible moderators of the action priming effect remain unclear. Nonetheless, it is important to note that the action priming experiment was always conducted after the 3D object perception experiment in the present study, as we were primarily interested in the development of the conflict cost between action representations. Although this should be relatively similar for all groups, the influence of the 3D object perception experiment on the action priming experiment cannot be ruled out.

Importantly, results showed a non-linear U-shape developmental trajectory of action priming effects between age 8 and adulthood. The U-shape curve was slightly asymmetric as reflected by an additional cubic trend. We found strong evidence for action priming effects in 8-year-olds, 14-year-olds and young adults but there was surprisingly no evidence for overall action priming in 10- and 12-year-olds. Interestingly, object usual grasp (clench vs. pinch) particularly influenced action priming effects in 10-year-olds, who were more sensitive to action primes for clenchable than pinchable objects. Results suggest important changes in the involvement of action representations in the categorization of visual objects at the end of elementary school. We will go back to this interpretation in the General Discussion.

Experiment 3: Simon task

Participants

The same 119 participants took part in Experiment 3.

Methods

Materials and procedure

We used the common Simon paradigm similar to those presented in literature (Hommel, 2011; Simon, 1969), It evaluates to what extent visual stimulus categorization is impeded when the location of the stimulus is in conflict with the location of the motor response required to perform the task. Spatial congruency effects in the Simon paradigm are assumed to reflect general conflict monitoring abilities.

Stimuli. Two alternative shapes, a white square or a white circle of 100 pixels, were positioned on a black background 300 pixels on the left or right of a white central fixation cross.

Procedure. The four picture stimuli were inserted in a spatial congruency paradigm. A central fixation cross was presented for 300 ms, followed by one of the four shape stimulus that remained on the screen until participants' response or for a maximum of 2000 ms. Participants had to classify the shape as a square or a circle irrespective of its left/right position by pressing two lateralized buttons. Since the Simon task involves shapes and not manipulable objects, the effector used for the response was not considered relevant and we opted for the most classical version of the paradigm using hand responses. The response mapping was counterbalanced across participants. Trials could be identified as congruent when shape position and button location were in accordance or incongruent when shape position and button location were not. A 500 ms black screen was presented between trials. In total, participants performed 20 practice trials and 258 experimental trials (half congruent and half incongruent) randomly separated into two testing blocks.

Data analysis

Bayesian generalized linear multilevel models with an ex-gaussian RT distribution and a log link function were used to evaluate the effects of the factors of interest on correct response times. Fixed effects included Age group (8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults), Spatial Congruency (congruent incongruent), Previous Trial (congruent, incongruent) and their interactions. The main effect of Spatial Congruency (i.e. the Simon effect) was the effect of interest. The congruency of the previous trial was added to the model in order to capture the classical modulations of Simon effects reported in the conflict monitoring literature (Gratton effect, cf. Gratton, Coles, & Donchin, 1992). The random effect structure of the model was kept maximal and included participants as random effect factor with random intercepts and random slopes for Spatial Congruency and Previous Trial.

Results

In the Simon paradigm, response times for incorrect responses and RTs below to 200 ms and RTs exceeding 5 times the median by age group were excluded from the analyses. Then RTs were trimmed by removing those 12.2 %, 7.3 %, 7.6 %, 5.4 % and 4.9 % of trials were excluded from further analyses, for 8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults, respectively. Mean RTs and standard deviations (SD) in the different conditions are reported in Table 3.

Irrespective of age, the Bayesian analysis of RTs showed strong evidence for a Simon effect (Est. of [log (Incong/Cong)] = 0.043, 95% CI = [0.033; 0.051], P+ = 1.00). Response times were overall 4.3% faster in the congruent than incongruent condition. There was also strong evidence for a modulation of the Simon effect by the congruency of the Previous Trial, with a greater Simon effect when the preceding trial was congruent than incongruent (Est. of [log(Incong/Cong| Previous Incong) – log(Incong/Cong | Previous Cong)] = -0.146, 95% CI = [-0.158; -0.134], P+ = 0).

Moreover, results from the Bayesian analysis did not support the presence of age-related differences in Simon effects. There was weak evidence for *linear, quadratic,* or *cubic* changes in the overall Simon effect (Est. for [linear coefficient of log(Incong/Cong) = 0.008, 95% CI = [-0.012; 0.030], P+ = 0.79; Est. for [quadratic coefficient of log(Incong/Cong) = -0.001,95% CI = [-0.021; 0.018], P+ = 0.45; Est. for [cubic coefficient of log(Incong/Cong) = -0.001,95% CI = [-0.022; 0.022], P+ = 0.50). Similarly, there was weak evidence for *linear, quadratic* or *cubic* changes in the Simon effect x Previous Trial interaction (Est. of linear coefficient = 0.001, 95% CI = [-0.025; 0.027], P+ = 0.52; (Est. of quadratic coefficient = -0.013,95% CI = [-0.040;

0.013], P+ = 0.16; (Est. of cubic coefficient = -0.011,95% CI = [-0.038; 0.015], P+ = 0.19). There was strong evidence for a Simon effect in each age group (all P+ values > 0.99).

Interim discussion

Results from the Simon experiment showed strong evidence for spatial congruency effects. As a whole, participants were about 25 ms (4.3%) faster to respond to basic shapes when the button press was performed on the same left/right side as the visual stimulus. The congruency effect was even stronger when the previous trial was congruent, reproducing the typical Gratton effect associated to this paradigm (Gratton et al., 1992). Yet results did not provide evidence for developmental changes in Simon effect amplitude between 8 and adulthood. Potential interpretations of the absence of aged-related changes in the Simon effect are beyond the scope of this study, but it leaves the question of the contribution of conflict monitoring abilities to the development of the conflict cost largely open. The next section focuses on between-subject variability across the different experiments, as individuals may show different levels of action activation and/or conflict monitoring abilities in each age group, beyond the presence or absence of a general age trend.

Relation between individual effects in the different experiments

The secondary goal of the study was to evaluate to what extent the magnitude of individual action priming effects and individual Simon effects could predict the magnitude of the conflict cost assessed in the main experiment. To this aim, Bayesian regression analyses were performed using the *brms* R package with action priming effects and Simon effects as predictors and conflict cost as the dependent measure. Following the group-level analyses conducted in each experiment, regression analyses were conducted on the log ratio of individual means in the relevant conditions. The possible presence of outliers to the regression was verified with the function "*check_outliers*" of the *performance* R package version 0.5.1. Three outliers (out of 119 participants) were detected (one in the 10-year-old group, one in the 12-year-old group and one in the adult group) and were excluded from the analyses. We expected positive relations between conflict costs and action priming effects and/or between conflict costs and Simon effects (the greater the activation of action representations and the greater the sensitivity to conflict, the greater the cost).

In 8-year-olds, the regression analysis showed moderate evidence for a positive relation between Simon effects and conflict costs (est. = 0.382, 95 % CI = [-0.089; 0.844], P+ = 0.95). However, there was weaker evidence for a relation between action priming effects and conflict costs in this group (est. = -0.119, 95 % CI = [-0.328; 0.010], P+ = 0.14). In contrast in 10-year-olds, the regression analysis highlighted strong evidence for a positive relation between action priming effects and conflict costs (est. = 0.472, 95 % CI = [0.087; 0.854], P+ = 0.99). Greater action priming predicted greater conflict cost in this group. Yet there was only weak evidence for a relation between Simon effects and conflict costs at 10 (est. = -0.021, 95 % CI = [-0.569; 0.526], P+ = 0.47). In the older groups, there were only weak evidence for relations between action priming and conflict costs or between Simon effects and conflict costs. The regression results for the different groups are presented in the Supplementary Figure.

General Discussion

The present developmental study aimed at identifying the developmental trajectory of the processing cost induced by the competition between action representations during visual object categorization. The conflict cost was assumed to result from the joint contribution of action representation activation and monitoring, two key processes in recent theoretical views on action selection and object embodiment (Cisek, 2007; Thill et al., 2013). As action representation activation and monitoring may follow different developmental timelines from childhood to adulthood, we anticipated a non-linear development of the conflict cost during this period. Five age groups (8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults) participated in a series of three experiments. The main experiment assessed age-related changes in the cost entailed by the perception of reachable objects with conflicting action representations in a 3D virtual environment (cf. Kalénine et al., 2016). Additional experiments evaluated the activation of action representations from visual objects with the action priming paradigm (Borghi et al., 2007; Godard et al., 2019) and general conflict monitoring abilities with the Simon paradigm (Hommel, 2011; Simon, 1969).

Non-linear changes in the conflict cost between structural and functional action representations between 8 and adulthood

The main results highlight a non-linear, U-shape developmental trajectory of the conflict cost between action representations between age 8 and adulthood. It is important to note that the identification of such a non-linear trajectory was made possible by assessing different age groups between mid-elementary school children and adults including young teenagers, which has rarely been done. Many studies (including ours) concluded about linear developmental changes after evaluating elementary school children and adults. In young adults, there was a conflict cost of 13 ms (2.3 % RT increase), which not surprisingly is a rather small effect, but nicely replicates our previous findings (Kalenine et al., 2016) with a different virtual set up and a different set of stimuli. Critically, results also support the presence of a conflict cost of about 40 ms in the youngest group (2.8 % RT increase). This result indicates that young children may activate both structural and functional action representations and are strongly impacted by the competition that may arise between them. Despite an increasing literature stressing the relevance of dividing object-related action representations into different subtypes, the sensitivity of young children to separate subtypes of action representations when processing objects had never been documented. In particular, as the motor experience of young children with object use is somewhat limited, it was still unclear whether they activated functional action representations from visual objects. Manipulation priming has been documented in children as young as 5 (Collette et al., 2016, Mounoud et al., 2007), but without dissociating structural and functional actions, it could result from the activation of one or both action representations. Here the emergence of a conflict cost suggests the co-activation of the both action representations and therefore indicates that functional action representations, dissociated from structural action representations, may be already activated from 8.

Results further indicate that the conflict cost then disappeared until adulthood. Age-related changes did not seem related to modifications in sole space perception. The distinction between reachable and non-reachable spaces was adequately performed by the different age groups. Moreover, the linear decrease of the effect of space with age, consistent with previous results (e.g., Gabbard, Cordova, & Ammar, 2007), did not match the developmental U-shape of the conflict cost. Regarding visual object processing, age did not impact the processing of conflictual and non-conflictual objects independently from space: judgments remained slower for conflictual than non-conflictual objects from 8 to adulthood. Thus, we explored the possibility that the U-shape developmental trajectory of the conflict cost is related to changes occurring from age 10 in the activation of action representations when processing visual objects, using the results of the second experiment. Results from the third experiment did not show any age-related changes and will not be further discussed.

Parallel developmental trajectory of conflict costs and action priming effects

Results highlight an important parallel between age-related changes in the selective cost observed during processing of reachable conflictual objects and action priming effects at the group and individual levels. At the group-level, both effects showed a non-linear, U-shape developmental trajectory that is difficult to attribute to the low-level characteristics of each task. In particular, results suggest a disappearance of both effects from 10 to 13 years of age. At the individual level, the magnitude of action priming effects predicted the amplitude of the conflict cost in 10-year-olds and only in this group. Together, these results suggest that developmental changes in the ability to activate action representations from visual objects are involved in the modifications of the cost entailed by the competition between conflicting action representations during object processing and highlight a shift in action-perception-object relations around 10. Then what happens to object-related action representations at the end of elementary school?

One possible interpretation is that activation of action representations from visual objects remains stable with age, but that the contribution of action representations to object categorization changes. During the years witnessing a high increase in verbal knowledge acquisition in school and education, the balance of motor and non-motor information in object concepts may change in the favor of non-motor information. Another possible interpretation is that development directly affects the activation of action representations, in relation to the important body-related changes that occur during early adolescence. Novel tool use and physical growth may affect the body schema, an internal representation of the body in action (Assaiante, Barlaam, Cignetti, & Vaugoyeau, 2014; Martel, Cardinali, Roy, & Farnè, 2016). The very rapid changes in the size and abilities of the child body from 10 may lead to limited motor simulation from visual stimuli and poor influence of action primes (especially for precision grasps associated to pinchable stimuli). Action priming effects have been found to be sensitive to the match between the representations of the participant's own body and the one currently perceived (Liuzza et al., 2012). Moreover, body schema disturbances impact motor control, and adolescents show a weaker coupling between perception and action than adults (Choudhury, Charman, Bird, & Blakemore, 2007). Accordingly, early adolescence may witness a temporary decrease of activation of action representations from visual objects.

The development of embodied cognition effects has received surprisingly very little attention in comparison to the rich documentation on embodied cognition effects in young adults, and results involving children and/or older adults do not orient towards a clear unique developmental trend through the lifespan (Loeffler, Raab & Cañal-Bruland, 2016). In the domain of language development for example, the influence of object sensorimotor properties on children's reading performance is not always visible when children start to learn to read and tends to increase with age (Dekker, Mareschal, Johnson, & Sereno, 2014; Wellsby & Pexman, 2014). Wellsby & Pexman (2014) showed that the potentiality of the body to physically interact with a word's referent facilitates word reading in 8-year-old children and in adults but not in 6-year-olds. Similarly, Dekker et al. (2014) reported category-specific sensorimotor brain activations when reading animal and tool names in adults but not in children aged 7 to 10 years. Rising embodied cognition effects during child development may be related to increased sensorimotor experience with objects with age. Yet the amount of past sensorimotor experience is probably not the sole contributing factor. In Dekker et al. (2014)'s study, the same children did activate category-specific sensorimotor brain regions when processing stimuli as pictures instead of words. The ability to simulate sensorimotor experience during the task may thus not be directly determined by the amount of past sensorimotor experience with objects. Younger children may actually be particularly efficient in using new sensorimotor simulations created on-line for the task, such as when evaluating whether an object displayed with a congruent or incongruent shape was present in the sentence they have just read (Engelen, Bouwmeester, de Bruin, & Zwaan, 2011). Thus, development of embodied cognition effects may combine the ability to create new sensorimotor simulations during the task (as when processing the structural shape of a visual object) and the ability to simulate past sensorimotor experience from the current stimulus (as here when simulating object use), leading in many occasions to non-linear developmental trajectories. Together, results from the present study suggest that the transition between elementary and middle school around 10 may correspond to an important restructuration period in action simulation from visual objects. Future research should focus on this age period to better understand the nature of the action-related changes that will impact object processing.

Conclusion

The present developmental study demonstrates that the competition elicited by the activation of conflicting action representations during object processing induces a cost in children as young as 8. Critically, the development of the conflict cost shows a U-shape trajectory between 8-year-old and adulthood with a disappearance of the detrimental effect between 10 and 14-year-old. The non-linear trajectory highlights separate periods of high sensitivity to competition between action representations and suggests complex changes in action representation activation during the early teenage years. The role of conflict monitoring abilities in the relation between object perception and action requires further investigation. Overall, the present findings provide novel insights into how age may change the impact of action representations on object processing and may help enriching theoretical views on action selection and object embodiment (Cisek, 2007; Smith, 2005a; Thill et al., 2013).

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Disclosure statement

The author(s) declared no conflicts of interest.

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Data availability statement

Raw data and full scripts for analysis of the three experiments are available here: https://osf.io/cvsdu/?view_only=22cd00af678047a4aadaaf2f41a89bc7

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Table 1. Mean RTs (and SD) in milliseconds as a function Space (R = Reachable, UR= Unreachable) and Object (C = Conflictual, NC = Non-conflictual) for each age group.

RC= Reachable Conflictual; RNC= Reachable Non-Conflictual; URC= Unreachable Conflictual; URNC= Unreachable Non-Conflictual.

	RC	**RNC**	**URC**	**URNC**	**R (all)**	**UR (all)**	**C (all)**	**NC (all)**	**(RC-RNC)-(URC-URNC)**
8-year-olds	1385 (250)	1336 (208)	1531 (259)	1525 (243)	1361 (228)	1528 (249)	1458 (262)	1430 (243)	43 (115)
10-year-olds	1168 (215)	1151 (205)	1335 269)	1319 (283)	1160 (213)	1329 (280)	1252 (261)	1237 (265)	0 (93)
12-year-olds	1138 (280)	1134 (283)	1231 (307)	1215 (281)	1136 (278)	1123 (291)	1184 (294)	1175 (282)	-11 (73)
14-year-olds	1023 (176)	993 (181)	1090 (193)	1063 (193)	1008 (177)	1076 (191)	1057 (186)	1028 (189)	3 (69)
young adults	852 (154)	834 (163)	886 (164)	882 (175)	843 (157)	885 (168)	870 (159)	858 (169)	13 (38)

Table 2. Model estimates, standard errors, and 95% credibility intervals for fixed effects in Experiment 1. Estimates are expressed in log-ratio.

Fixed effects	**Estimate**	**Error**	**95% CI**
Omnibus effects of Space, Object Type, Space x Object Type, Space x Object Type x Task			
Age intercept x Space	0.086	0.007	[0.072 ; 0.100]
Age intercept x Object Type	0.023	0.003	[0.017 ; 0.030]
Age intercept x Space x Object Type	0.013	0.006	[0.003 ; 0.025]
Age intercept x Space x Object Type x Task	-0.033	0.011	[-0.054 ; -0.012]
Age-related effects of Space, Object Type, Space x Object Type, Space x Object Type x Task			
Age linear x Space	-0.065	0.014	[-0.092 ; -0.036]
Age quadratic x Space	-0.002	0.015	[-0.032 ; 0.027]
Age cubic x Space	0.012	0.015	[-0.017 ; 0.042]
Age linear x Object Type	0.000	0.007	[-0.012 ; 0.013]
Age quadratic x Object Type	0.002	0.007	[-0.011 ; 0.015]
Age cubic x Object Type	-0.008	0.008	[-0.023 ; 0.008]
Age linear x Space x Object Type	0.004	0.012	[-0.002 ; 0.026]
Age quadratic x Space x Object Type	0.021	0.012	[-0.003 ; 0.045]
Age cubic x Space x Object Type	-0.016	0.013	[-0.043 ; 0.009]
Age linear x Space x Object Type x Task	0.011	0.023	[-0.034 ; 0.056]
Age quadratic x Space x Object Type x Task	0.018	0.023	[-0.027 ; 0.064]
Age cubic x Space x Object Type x Task	0.016	0.025	[-0.034 ; 0.065]
Simple effects of Space x Object Type interaction in each age group			
Space x Object Type in 8 year-olds	0.028	0.013	[0.003 ; 0.054]
Space x Object Type in 10 year-olds	-0.007	0.015	[-0.038 ; 0.022]
Space x Object Type in 12 year-olds	0.007	0.013	[-0.018 ; 0.031]
Space x Object Type in 14 year-olds	0.016	0.013	[-0.010 ; 0.041]
Space x Object Type in adults	0.023	0.009	[0.006 ; 0.040]

Table 3. Mean RTs (and SD) in milliseconds as a function of Action priming (Action, Neutral) in the Action Priming paradigm and as a function of Spatial Congruency in the Simon paradigm.

	Action priming			**Simon**		
	Neutral primes	**Action primes**	**Neutral-Action primes**	**Incongruent**	**Congruent**	**Incongruent-Congruent**
8-year-olds	1187	1137	50	806	781	25
	(219)	(219)	(151)	(95)	(99)	(48)
10-year-olds	945	943	2	703	676	27
	(181)	(173)	(115)	(120)	(107)	(44)
12-year-olds	910	932	-21	643	613	30
	(236)	(269)	(113)	(104)	(94)	(41)
14-year-olds	697	674	23	544	522	22
	(131)	(129)	(60)	(77)	(81)	(33)
young adults	616	597	19	483	460	23
	(102)	(90)	(39)	(49)	(52)	(27)

Figure 1

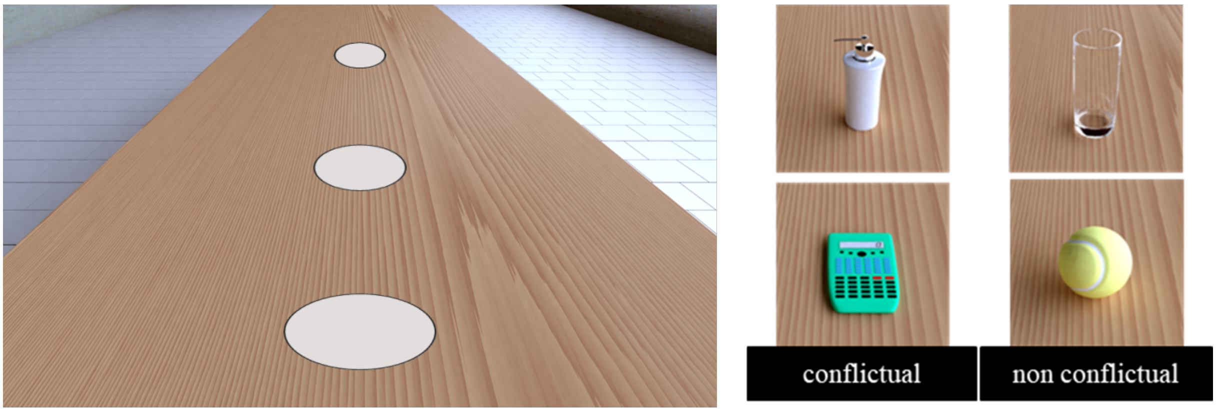

Figure 2

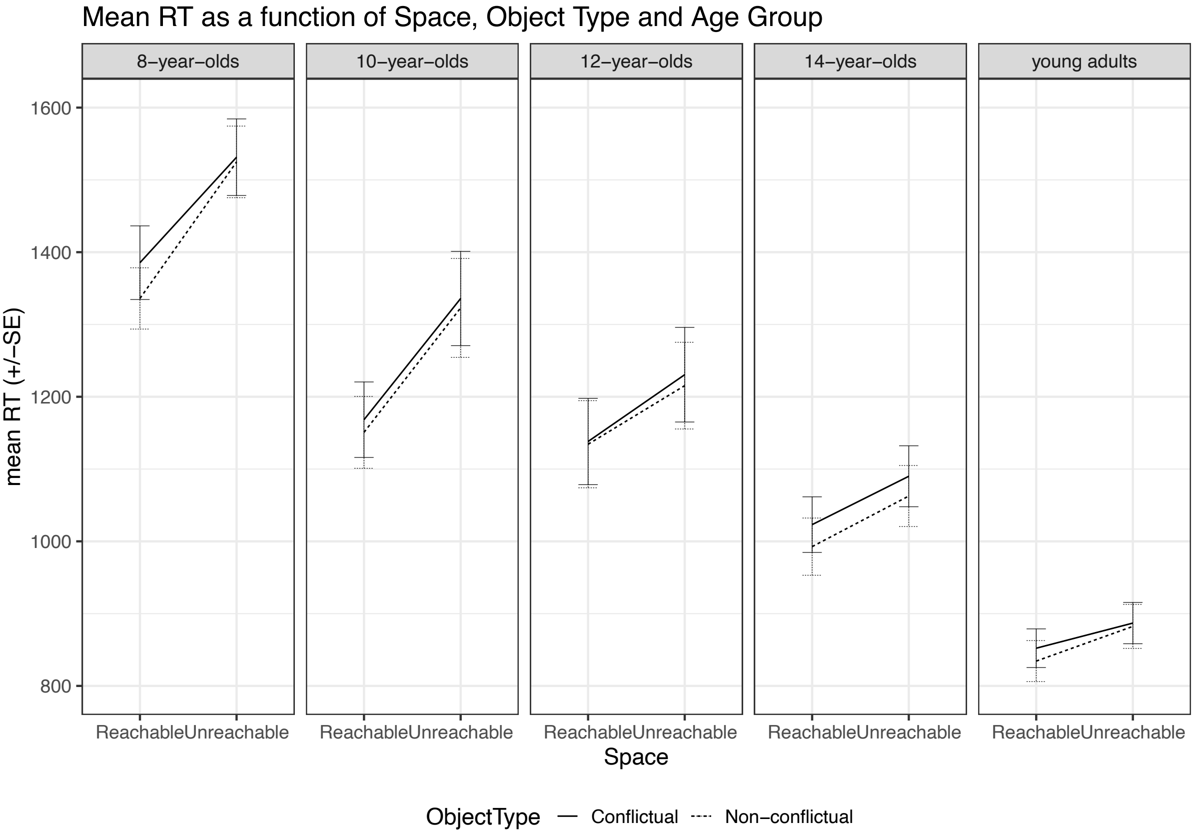

Figure 3

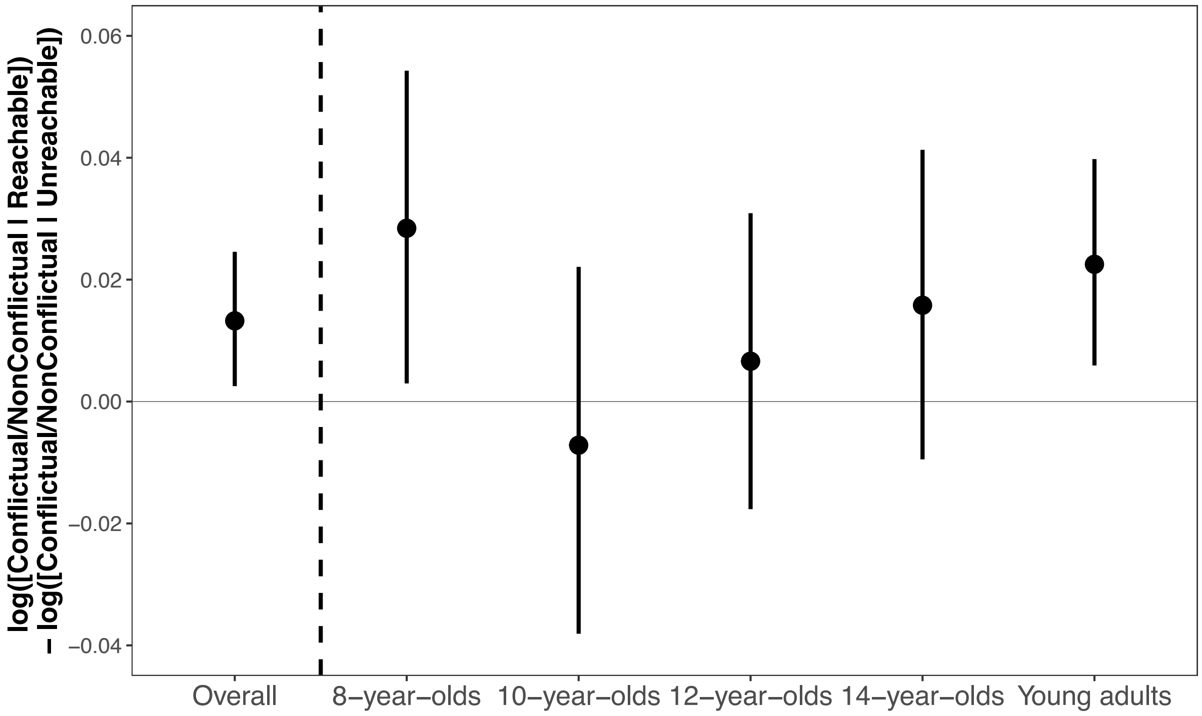
log([Conflictual/NonConflictual | Reachable])
– log([Conflictual/NonConflictual | Unreachable])
0.06
0.04
0.02
0.00
−0.02
−0.04
Overall
8−year−olds
10−year−olds
12−year−olds
14−year−olds
Young adults

Figure 4

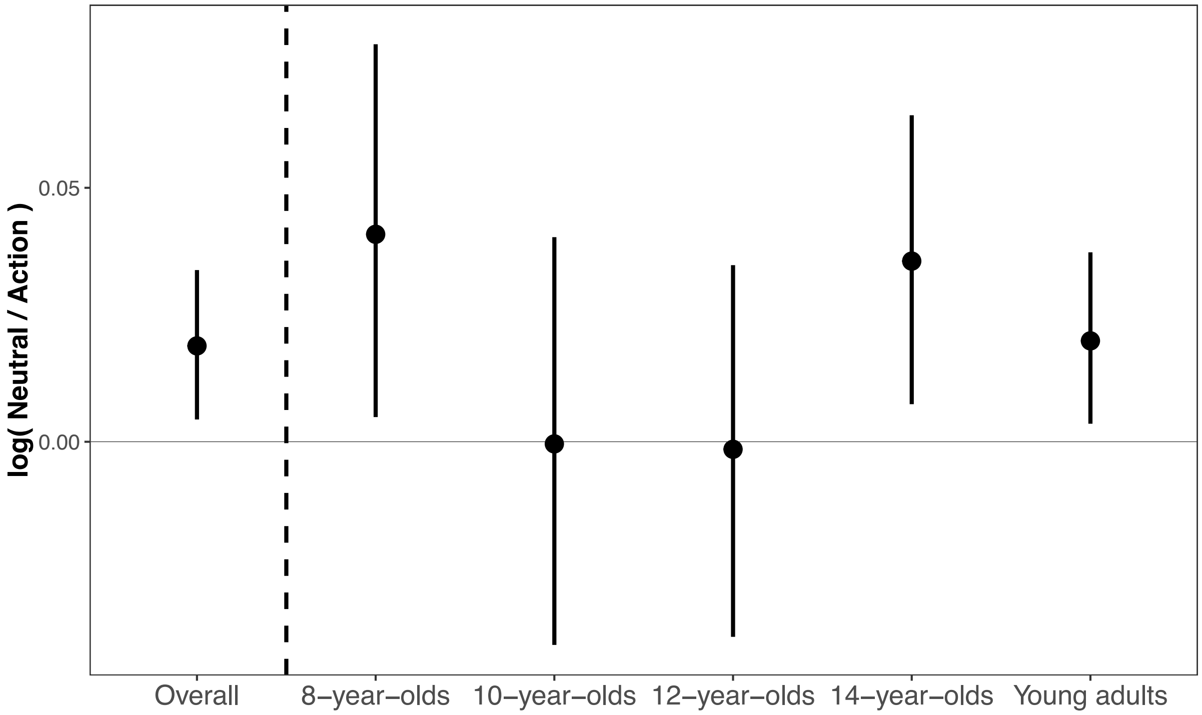

Figure captions

Figure 1. Experimental setting in the 3D environment. On the left are represented the different distances (e.g., near, limit of reachability, far) at which stimuli are presented in the virtual scene. On the right are displayed examples of conflictual and non-conflictual objects from both object categories (top: kitchen objects; bottom: non-kitchen objects). Participants' task was to judge object category ("is it a kitchen object?") or object reachability ("is it reachable?"), responding with foot pedals.

Figure 2: Mean response times and standard errors as a Function of Space (Reachable, Unreachable), Object Type (Conflictual, Non-conflictual) and Age Group (8-year-olds, 10-year-olds, 12-year-olds, 14-year-olds and young adults) in Experiment 1.

Figure 3: Overall mean and 95% CI of conflict cost estimate (left) and conflict cost estimates for the different age groups (right). The conflict cost is computed as the difference between the log-ratio of response time expected values to conflictual versus non-conflictual objects when presented within reach, in comparison to the same log-ratio when objects are presented out of reach.

Figure 4. Overall mean and 95% CI of action priming effect estimate (left) and action priming effect estimates for the different age groups (right). The action priming effect is computed as the log-ratio of response time expected values to objects preceded by neutral primes versus objects preceded by action primes.