Consciousness and Cognition 52 (2017) 104–114

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Intentional binding as a marker of agency across the lifespan

Annachiara Cavazzana[a,b,c,*], Chiara Begliomini[a,d], Patrizia Silvia Bisiacchi[a,d]

[a] Department of General Psychology, University of Padova, via Venezia, 8, Padova, Italy
[b] Smell & Taste Clinic, Department of Otorhinolaryngology, TU Dresden, Fetscherstrasse 74, 01307 Dresden, Germany
[c] Gösta Ekman Laboratory, Department of Psychology, Stockholm University, Frescati Hagväg 9A, 106 91 Stockholm, Sweden
[d] Center for Cognitive Neuroscience, University of Padova, Via Venezia, 8, Padova, Italy

ARTICLE INFO

Keywords:
Sense of agency
Intentional binding
Lifespan
Responsibility
Frontal lobe

ABSTRACT

The feeling of control over actions and their external effects is known as Sense of Agency (SoAg). People usually have a distinctive SoAg for events caused by their own actions. However, if the agent is a child or an older person, this feeling of being responsible for the consequences of an action may differ from what an adult would feel. The idea would be that children and elderly may have a reduced SoAg since their frontal lobes are developing or have started to loose their efficiency. The aim of this study was to elucidate whether the SoAg changes across lifespan, using the Intentional Binding (i.e., the temporal attraction between a voluntary action and its sensory consequence) as implicit measure. Data show that children and elderly are characterized by a reduced SoAg as compared to adults. These findings provide a fundamental step in the characterization of SoAg dynamics throughout individuals' lifetime.

1. Introduction

Our voluntary actions are typically accompanied by a Sense of Agency (SoAg; Haggard & Tsakiris, 2009). We feel that we can choose and control our own actions and consequently the outside world. Historically, SoAg has been a topic of interest mainly to philosophers (e.g., Gallagher, 2000; Pacherie, 2008), but over recent years it has also received attention from psychology and cognitive neuroscience researchers given its potential role in many aspects of our everyday life. In fact, SoAg is deeply entwined with our notions of freedom and is intrinsic to ethical and law questions concerning responsibility and guilt (e.g., Haggard & Chambon, 2012; Moretto, Walsh, & Haggard, 2011). Indeed, when we voluntarily perform actions, we feel responsible for them and for their consequences. The experience of agency is therefore a complex and multifaceted phenomenon, which requires not only a plan to perform a goal-directed action, but also the ability to properly identify the consequences of that behaviour in the external world, avoiding and inhibiting erroneous and maladaptive behaviours (Haggard & Tsakiris, 2009). These high-level cognitive abilities are usually part of the executive functions (EFs), supported by the functionality of frontal areas (Stuss & Levine, 2002). Even though there are no studies which have directly linked the SoAg to these cognitive functions (i.e., EFs), general scientific progress in recent years has nevertheless elucidated a clear picture of the neural bases of the SoAg, pinpointing an involvement of frontal, prefrontal and parietal areas in this phenomenon (e.g., Cavazzana, Penolazzi, Begliomini, & Bisiacchi, 2015; Khalighinejad, Di Costa, & Haggard, 2016; Khalighinejad & Haggard, 2015; Kühn, Brass, & Haggard, 2013; Moore, Ruge, Wenke, Rothwell, & Haggard, 2010; Renes, van Haren, Aarts, & Vink, 2015). As recently reported by Haggard (2017) in an elegant review, the experience of agency is mediated by the connectivity between frontal and prefrontal areas – responsible for planning and initiating actions – and parietal regions which are involved in monitoring the perceptual events. Their involvement is also supported by clinical studies which revealed that an

* Corresponding author at: Department of General Psychology, University of Padova, Via Venezia 12, 35131 Padova, Italy.
E-mail address: annachiara.cavazzana@gmail.com (A. Cavazzana).

http://dx.doi.org/10.1016/j.concog.2017.04.016
Received 17 November 2016; Received in revised form 1 April 2017; Accepted 24 April 2017

impaired functionality of such areas is associated with pathologies characterized by a lack of agency (e.g., corticobasal syndrome: Wolpe et al., 2013; schizophrenia: Renes et al., 2016). Another example of inefficiency of these regions might be represented by both healthy children and elderly people. It is well known that the frontal cortex is subjected to dramatic age-related modifications (for a review, see: West, 1996): it is the last cortical area to mature in children and among the first to be impaired in aging (e.g., Casey, Tottenham, Liston, & Durston, 2005; Raz, 2000). Usually, these changes in brain structure and functionality inevitably impact on cognitive abilities as well, in particular on EFs, which are mediated by frontal lobes' integrity and activity. A considerable body of research convincingly shows that there are systematic, age-related improvements in EFs during childhood and adolescence, coinciding with growth spurts in the maturation of the frontal lobes (e.g., Zelazo & Müller, 2002). Likewise, a decrease of EFs during normal aging, even in the absence of pathologies, has been demonstrated (e.g., Zelazo, Craik, & Booth, 2004). In light of these assumptions, one might expect changes in the processing of agency in these two populations. However, how this capacity changes across the lifespan has not yet been addressed and it constitutes an open, pertinent issue, given the impact of SoAg in social and legal aspects of life. As mentioned above, SoAg implies individual responsibility for the consequences of one's own actions (Frith, 2014; Moll et al., 2007) and in many countries, the law requires that the individual be fully responsible and aware of the consequences of his/her actions (Frith, 2014; Haggard & Chambon, 2012; Moretto et al., 2011). A first attempt to study whether SoAg differs in children and elderly people in respect to young adults was conducted by Metcalfe, Eich, and Castel (2010). The Authors tried to resolve this issue investigating the different level of metacognitive awareness of agency across the lifespan. They used an explicit computer task previously adopted to study the metacognition of agency in young adults (Metcalfe & Greene, 2007). Participants had to move the mouse to get the cursor to touch X's and avoid the O's which streamed from the top of a computer screen. Afterwards, they were asked to make *judgments of agency* (i.e., how in control he/she felt) and *judgments of performance*. Objective control was either undistorted (i.e., participant had perfect control of the mouse), or distorted by (i) 'turbulence' (i.e., random noise was added to the position of the mouse to produce the position of the cursor on the screen, limiting participant's control), (ii) 'lag' between the mouse and cursor movements (of 250 or 500 ms), or (iii) 'magic,' (i.e., an increased radius around the X's such that the person would be credited with touching an X even if they had not touched it). Authors observed that young adults were the most sensitive to discrepancies in control over their own actions compared to both children (8–10 years old) and older adults (mean age 75). This finding suggest that SoAg could evolve across the lifespan, changing our skills to link our actions with their consequences. More recently, van Elk, Rutjens, and van der Pligt (2015) investigated the possible role of SoAg in the development of illusory control (i.e., the erroneous belief that one's actions can cause a certain outcome, even if that outcome is uncontrollable and determined by chance) in 7–12-year-old children and in young adults. Participants were asked to play a computerized card guessing game in which they were required to select a face-down card from a deck of two rapidly flashing cards on a computer screen. Following their selection of a card, a randomized outcome was presented and participants were required to indicate to what extent they believed the card was selected by themselves or by the computer. The authors manipulated the congruence of the outcome with participants' initial choice (i.e. congruent or incongruent) and the valence of the presented outcome (i.e. positive or negative). The analysis focused on perceived control throughout the card guessing game as a measure of 'illusory control', and on perceived control as a function of action outcome, as a measure of the SoAg. They observed that the illusion of control throughout the card guessing game was more enhanced for younger (< 8 years old) compared to older children (> 8 years old) and more pronounced for children compared to adults. Regarding SoAg, both adults' and children' agency ratings were similarly affected by the congruence between performed and observed outcomes (e.g., when a temporal delay or spatial deviation was introduced) in line with adult studies (e.g., Aarts, Custers, & Marien, 2009; Daprati et al., 1997). However, this latter study did not consider older participants. Although the studies by Metcalfe et al. (2010) and van Elk et al. (2015) represent the first attempts to investigate age-related differences in the SoAg, only explicit agency measures were considered. However, explicit measures of agency are usually very prone to be influenced by individual differences related to cognitive capacities or personality, and to a lack of subjectivity insights (e.g., Gawronski, LeBel, & Peters, 2007). In addition, this sort of measure reflects very little about the SoAg, since it does not capture the feeling of agency that accompanies normal voluntary actions. Recently, our group adopted implicit measuring of the SoAg with children (Cavazzana, Begliomini, & Bisiacchi, 2014). The classical Intentional Binding effect (IB – Haggard, Clark, & Kalogeras, 2002) was considered: the IB refers to the temporal compression between a voluntary action and its ensuing sensory effect. In other words, when a voluntary action is followed by a sensory effect (e.g., a sound), people tend to perceive the onset of the voluntary action later in time, towards its effect as compared to a baseline condition in which only the voluntary action is present (i.e., action binding). On the other hand, the sound triggered by the voluntary action is perceived earlier in time towards its voluntary action, as compared to a baseline condition in which only the sound is present. This bias to perceive actions and effects closer in time than they actually are has been observed only when the action is intentional. Indeed, it does not happen when the first event is unrelated to the participants' will. For this reason, IB has been considered a reliable implicit measure of agency. By taking advantage of the implicit nature of this measure, differences in the processing of agency in children as compared to young adults were demonstrated (Cavazzana et al., 2014). In particular, we found that children showed a reduced temporal compression (i.e., IB) as compared to young adults. Starting from these results, we decided to extend the investigation to elderly people. The general purpose of the present work was therefore to explore how IB, as an implicit measure of SoAg, can evolve across the lifespan, avoiding the limits of verbal reports that characterize the explicit level of SoAg. Based on previous studies (e.g., Cavazzana et al., 2014; Metcalfe et al., 2010; Moore, 2016), we expected the IB effect to show different features in children and elderly people as compared to young adults. More precisely, we expected the IB effect to be weaker in children and elderly as compared to young adults.

2. Methods

2.1. Participants

A total of sixty participants were recruited for this study. They were subdivided into three groups according to their ages: (1) a group of twenty young adults (15 females; age range: 22–30; mean age in years: 23.75, SD: 2.53; education in years: 16.67, SD: 0.98); (2) a group of twenty children (16 females; age range: 8–11; mean age in years; 10.05, SD: 0.94; education in years: 5.1, SD: 0.85); (3) twenty elderly people (12 females; age range: 66–76; mean age in years: 69.75, SD: 3.39; education in years: 15.1, SD: 4.14). All the participants were right-handed, as measured by the Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected-to-normal vision, and did not present neurological, neuropsychological or psychiatric pathologies. On the basis of these exclusion criteria, two elderly persons (Mini Mental State Examination, MMSE $<$ 24; Folstein, Folstein, & McHugh, 1975) were excluded. In addition, data of one child were not included because the task was interrupted by the participant. The final cohort consisted of 19 children (15 females; age range: 8–11, mean age in years: 10, SD: 0.94; education in years: 5.05, SD: 0.85) and 18 elderly people (11 females; age range: 66–76, mean age in years: 69.78, SD: 3.21; education in years: 14.78, SD: 4.25). The study was designed and carried out in accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee of the University of Padua. All the participants were naïve to the purpose of the experiment and gave their informed, written consent to participate in the study. For children, the informed consent was obtained from the parents.

2.2. Stimuli, apparatus and procedure

IB was assessed using the paradigm developed by Cavazzana et al. (2014). Participants were asked to passively observe a stream of unpredictable white, capital consonants at the centre of a black screen. In order to prevent the participants from responding immediately after seeing the letters, a series of randomized white numbers was displayed before the letters were presented. Each number and letter was presented separately and lasted for 150 ms, without time gaps in between (Fig. 1). The experiment consisted of four baseline conditions (BCs) and six experimental conditions (ECs), for a total of ten conditions (Table 1).

With regard to the BCs (Fig. 2), only one event among voluntary action, involuntary action, tone, or control tone occurred per condition. In the case of "voluntary action" condition, it was the participant who decided when to perform the key-press; in all the other BCs (i.e., involuntary action, tone, control tone), the event was triggered randomly by the computer. In BCs, the participants were supposed to remember which consonant was on the screen when (1) they made a free voluntary key-press with their right index finger (acting as a baseline for voluntary action condition). In this case, they were explicitly asked to press the spacebar at a time of their own choice, without any time constraints. The only limit which was imposed to them was to wait until the letters' appearance before making their action, in order to avoid response anticipation (i.e., a key-press performed immediately after the trial onset); (2) they felt their right index finger being passively pushed down by a squared shaped mechanical device (acting as the baseline for involuntary action condition), applied to the participant's right index finger. For the involuntary condition, the participant's hand was placed on the top of the device and her/his right index finger was fixed on a keyboard button placed on its left corner. The device was connected and activated by computer at a random interval after the trial's onset. When the computer gave the input, the key and,

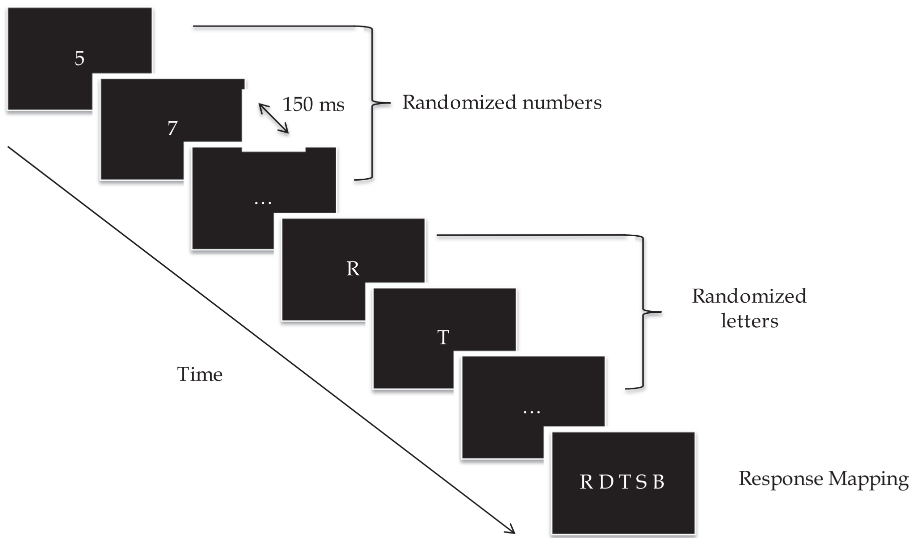

Fig. 1. Schematic illustration of the task structure. Participants passively observed a series of numbers and letters that was updated every 150 ms. The frame with "…" here represents the continuous flow either of numbers or letters. After the appearance of the event of interest (e.g., voluntary action, involuntary action, tone, control tone) a response mapping was presented and participants chose the letter that was on the screen when the event of interest occurred (e.g., voluntary action, involuntary action, tone, control tone).

Table 1
Conditions (Baseline and Experimental) and the judged event by the participants in each condition.

Condition	Judged Event
Baseline Conditions	
(1) Voluntary Action	Voluntary Action
(2) Involuntary Action	Involuntary Action
(3) Tone	Tone
(4) Control Tone	Control Tone
Experimental Conditions	
(5) Voluntary Action – 250 ms – Tone	Voluntary Action
(6) Voluntary Action – 250 ms – Tone	Tone
(7) Involuntary Action – 250 ms – Tone	Involuntary Action
(8) Involuntary Action – 250 ms – Tone	Tone
(9) Control Tone – 250 ms – Tone	Control Tone
(10) Control Tone – 250 ms – Tone	Tone

With regard to the BCs, only one event occurred per condition (e.g., voluntary action, involuntary action, tone, control tone). For the ECs, two events occurred per condition. The time interval between the first event (the voluntary action, the involuntary action, or control tone) and the second event (tone) was set at 250 ms.

consequently, the right index finger pushed down, giving the participant the same physical perception as the voluntary key-press; (3) they heard an auditory stimulus presented through headphones (1000 Hz, 100-ms duration; baseline for tone condition: tone); (4) they heard another auditory control stimulus presented by headphones (same duration as the tone but with a different pitch; baseline for tone control condition: the control tone).

For the ECs, two events occurred per condition (Fig. 3). The participants had to judge: (5) the onset of the voluntary action that produced the tone; (6) the onset of the tone caused by the voluntary action; (7) the onset of the involuntary action that was followed by the tone; (8) the onset of the tone activated by the involuntary action; (9) the onset of the control tone that was followed by the tone; (10) the onset of the tone activated by the control tone.

The time interval between the first event (the voluntary action, the involuntary action, control tone) and the second event (tone) was set at 250 ms. Conditions involving the 'involuntary action' and 'control tone' were introduced as control conditions in order to exclude the possible presence of IB in such conditions. In all conditions, the stimuli were presented randomly, between 3 and 8 s after the trial onset (i.e., number onset). The stream of letters stopped randomly between 1.5 and 5 s after the event of interest. At the end of each trial, a set of response options (called 'response mapping') appeared on the screen. Five letters were presented on the screen, which included the target letter (i.e., the letter that was on the screen at the actual appearance of the event of interest) and two letters immediately before as well as two letters immediately after the target letter in the series of letters. All the letters within the response mapping were presented in a different random order. After each trial, the participants were expected to choose the correct consonant using the keyboard with their left hand. Thirty-three trials per condition were administered, for a total of 330 trials. The first three trials of each condition were discarded to allow for familiarization and were not included in the analysis. Each participant performed all of the conditions (BCs and ECs) in a different, random order over a single session.

2.3. Calculation of the IB

For each trial, a judgment error (JE) was calculated, which is the difference between the actual time the event occurred and the time it was perceived to occur. A negative JE was interpreted as anticipatory awareness of events (i.e., the participants perceived the event happening *before* it actually did), while a positive JE was interpreted as delayed awareness (i.e., the participants perceived the

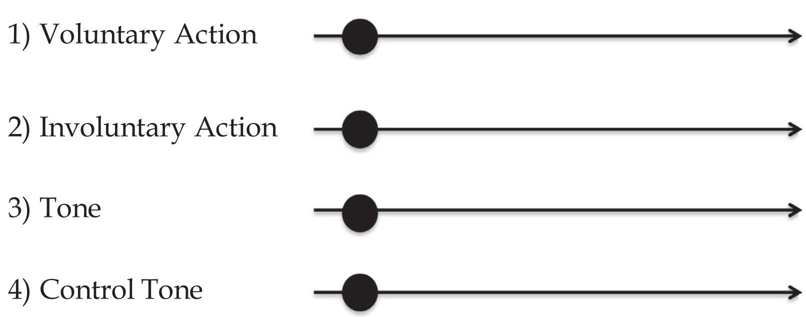

Fig. 2. Schematic representation of the BCs in which only one event (i.e., voluntary action, involuntary action, tone, control tone) occurred per condition. While they were viewing the series of numbers and letters, the participants had to remember which consonant was on the screen when: (1) they made a voluntary key-press; (2) they felt their right index finger being pushed down passively; (3) they heard the tone; and (4) they heard the control tone.

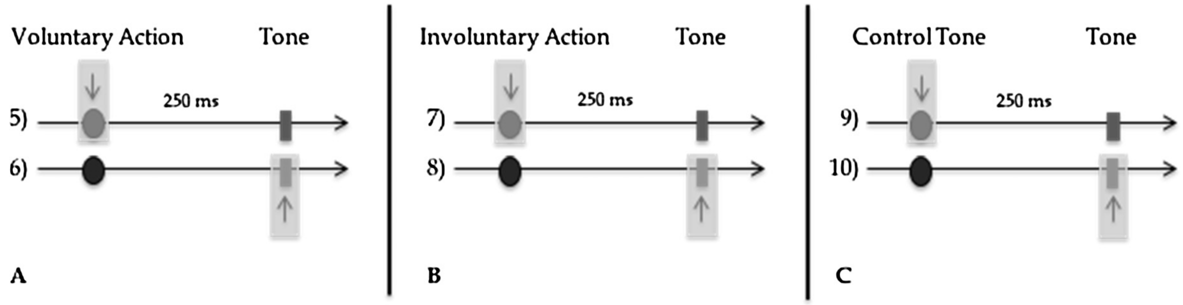

Fig. 3. Schematic representation of the ECs. (A) The participants judged the letter that was on the screen either when they made the voluntary action (5) or heard the tone (6). (B) Participants judged the letter that was on the screen either when they felt their right index finger moved down passively (involuntary action; 7), or heard the tone (8). (C) Participants judged the letter that was on the screen either when they heard either the control tone (9) or the tone (10).

event happening *after* it actually did). A final mean judgment error (mJE), including both negative and positive values, was calculated. It is important to underlie that the computed dependent variable reports the accuracy of letter choice and does not implicate any temporal precision in milliseconds; however, it gives anyway an indication of time: for example, selecting the value "−1" would indicate that participant thought the event occurred about 150 ms prior its actual appearance. Baseline judgments usually vary widely both across people and groups (Haggard, Martin, Taylor-Clarke, Jeannerod, & Franck, 2003; Haggard et al., 2002) and may reflect individual strategies either in the attention paid to the letters or in perceptual processes. In order to control for such individual differences, the differences between the mJE of an identical physical event in two different contexts (the BCs and ECs) were calculated (i.e., the perceptual shifts) by subtracting the mJE of each event in the BC (voluntary action, involuntary action, tone, or control tone) from the mJE of the same event in the EC. For example, the shift of the action towards the tone (i.e., action binding) was calculated by subtracting the mJE of the voluntary action in the BC from the mJE of the voluntary action in the EC, whereas the shift of the tone towards the action (i.e., effect binding) was found by subtracting the mJE of tone in the BC from the mJE of the same tone in the EC. Finally, an overall binding measure (e.g., Haggard & Clark, 2003; Haggard et al., 2002) was also computed by combining the first (i.e., the action binding) and the second event (i.e., the tone binding). By calculating 250 ms – (action binding – effect binding), the obtained value represents the perceived linkage between an action and an effect and provides an implicit measure of SoAg.

2.4. Statistical analyses

Analyses were carried out by using both Statistical Package for Social Sciences (SPSS) and R software package (http://cran.r-project.org). Violin plots with a Kernel distribution applied were used to represent data (Allen, Erhardt, & Calhoun, 2012). To analyse data two main analyses were run: (i) univariate Analysis of Variance (ANOVA) was used to analyse differences in BCs between groups; (ii) in order to control for individual differences, perceptual shifts were calculated using repeated-measures ANOVA with 'type of context' (voluntary, involuntary, sensory) and the 'judged event' (either the first or the second) as within-participants factor. Greenhouse-Geisser correction was applied to the degrees of freedom of F statistics when the Mauchly's Test of Sphericity showed that the sphericity assumption was violated (alpha level: $p < 0.05$). *Post-hoc* comparisons were then used to explore the means of interest and Bonferroni correction for multiple comparisons was applied (alpha level: $p < 0.05$). In addition, non-parametric correlations (Spearman's rank correlation coefficient) were used in order to measure possible associations between IB and neuropsychological test scores.

2.5. Neuropsychological measures

All participants underwent basic neuropsychological screening in order to exclude participants with cognitive issues, which might interfere with the task. The neuropsychological evaluation of the children included assessment of: (i) problem solving and abstract reasoning using the Coloured Progressive Matrices (Italian standardization: Pruneti et al., 1996); (ii) sustained and selective attention (Bells Test: Biancardi & Stoppa, 1997); (iii) divided attention (Trial Making Test: TMT; forms A, AB, and B; Scarpa et al., 2006). The tests administered to elderly people included: (i) the MMSE; (ii) the Digit Span for memory assessment (included in the Brief Neuropsychological Examination 2; BNE-2; Mondini, Mapelli, Vestri, et al., 2011); (iii) TMT-A and TMT-B to assess the cognitive domain of attention and EFs (always included in the BNE-2); (iv) the Frontal Assessment Battery to evaluate frontal lobe functions and motor skills (FAB: Appollonio et al., 2005).

3. Results

All the participants included in the final sample obtained normal scores on neuropsychological tests. Tables 2–4 summarize the mJEs, perceptual shifts, and overall binding in young adults, children and elderly people, respectively.

The degree of binding was compared among the three groups in order to detect any possible difference in IB. First, BCs were

Table 2
mJEs, perceptual shifts and overall binding in young adults.

	Event Judged	mJE (ms) ± sd	Mean Shift (ms) ± sd	Mean Overall Binding (ms) ± sd
Baseline Conditions				
(1) Voluntary Action	Voluntary Action	10.5 ± 61.15		
(2) Involuntary Action	Involuntary Action	70 ± 70.52		
(3) Tone	Tone	53 ± 50.51		
(4) Control Tone	Control Tone	48 ± 46.58		
Experimental Conditions				
(5) Voluntary Action – Tone	Voluntary Action	88.5 ± 76.64	78 ± 51.03	70.25 ± 73.13
(6) Voluntary Action - Tone	Tone	−38.75 ± 61.62	−91.75 ± 66.91	
(7) Involuntary Action - Tone	Involuntary Action	78.25 ± 13.52	8.25 ± 38.94	187.25 ± 105.2
(8) Involuntary Action - Tone	Tone	10.5 ± 94.51	−42.5 ± 90.82	
(9) Control Tone - Tone	Control Tone	29.5 ± 48.12	−18.5 ± 43.8	217 ± 111.05
(10) Control Tone - Tone	Tone	21 ± 62.78	−32 ± 65.28	

analysed using univariate ANOVA. No differences among the three groups were observed in the perception of voluntary action, $F(2,54) = 1.17$, $p = 0.318$, or in the involuntary action, $F(2,54) = 1.75$, $p = 0.184$. However, significant differences emerged with regard to tone, $F(2,54) = 11.15$, $p < 0.001$, $\omega^2 = 0.26$ and control tone $F(2,54) = 5.34$, $p = 0.008$, $\omega^2 = 0.13$. Regarding the temporal perception of tone, *post hoc* tests – with Bonferroni correction applied – revealed a significant difference between adults and elderly people (−60 vs 8.33 ms respectively, $p = 0.011$, mean difference: 4.67, 95% CI: 8.18, 81.16) and between children and elderly (78.15 vs 8.33 ms respectively, $p < 0.001$, mean difference: 69.82, 95% CI: 32.88, 106.77). Concerning the temporal perception of control tone, a significant difference emerged only between children and elderly (81.57 vs 27.5 ms respectively, $p = 0.006$, mean difference: 54.08, 95% CI: 12.67, 95.49). According to the results and in line with other studies (e.g., Haggard et al., 2003; Moore et al., 2010), the participants differed markedly in their temporal perception of these baseline events, reflecting individual strategies either in the attention paid to the stream of letters or in perceptual processes. In order to control and remove these individual differences, perceptual shifts were analysed using 3 ('type of context') × 2 ('judged event') repeated-measures ANOVA, using the group (young adults, children and elderly) as between-factor. First, a non-significant effect of group was detected, $F(2,54) = 0.740$, $p = 0.482$, $\eta_p^2 = 0.027$. Instead, significant main effects of both 'type of context', $F(2,108) = 6.44$, $p = 0.002$, $\eta_p^2 = 0.107$, and 'judged event', $F(1,54) = 70.34$, $p < 0.001$, $\eta_p^2 = 0.566$, were observed. Participants tended to have a general reduced anticipated temporal perception regarding the events within the voluntary action context (−9.79 ms, 95% CI: −22.85, 3.27) as compared to both the involuntary (−29.53 ms, 95% CI: −39.41, −19.66; $p = 0.015$) and the sensory contexts (−29.94 ms, 95% CI: −39.43, −20.46; $p = 0.01$). No significant differences emerged between the involuntary and the sensory contexts ($p = 1.000$). Regarding the 'judged event', the first event was shifted towards the second one (11.55 ms, 95% CI: 2.37, 20.73) and vice versa (−57.73 ms, 95% CI: −71.19, −44.27; $p < 0.001$). Most importantly, the interaction between 'group', 'type of context' and 'judged event' was significant, $F(4,108) = 3.99$, $p = 0.005$, $\eta_p^2 = 0.129$. Differences between groups were significant only regarding the *action binding* within the voluntary action context (i.e., the shift of the voluntary action towards the tone, Fig. 4). Specifically, action binding was significantly different between young adults and children ($p = 0.034$; 95% CI: 3.56, 122.44; mean difference = 63), but not between young adults and elderly ($p = 0.514$) or between elderly and children ($p = 0.728$). Also, the overall binding was compared among the three groups. No effect of group was observed, $F(2,54) = 1.74$, $p = 0.186$, $\eta_p^2 = 0.06$, while a main effect of overall binding emerged, $F(2,108) = 9.58$, $p < 0.001$, $\eta_p^2 = 0.151$. Temporal compression within the voluntary action context was significantly different as compared to both the involuntary action context ($p = 0.007$) and the sensory context ($p = 0.001$). No differences emerged between the two control contexts, namely the involuntary and the sensory context ($p = 0.600$). Most importantly, a significant interaction between the overall binding and the group emerged, $F(4,108) = 3.48$, $p = 0.010$,

Table 3
mJEs, perceptual shifts and overall binding in children.

	Judged Event	mJE (ms) ± sd	Mean Shift (ms) ± sd	Mean Overall Binding (ms) ± sd
Baseline Conditions				
(1) Voluntary Action	Voluntary Action	−20.79 ± 68.01		
(2) Involuntary Action	Involuntary Action	82.63 ± 46.92		
(3) Tone	Tone	78.16 ± 23.05		
(4) Control Tone	Control Tone	81.58 ± 48.13		
Experimental Conditions				
(5) Voluntary Action - Tone	Voluntary Action	−5.79 ± 79.09	15 ± 76.08	170.26 ± 98.9
(6) Voluntary Action - Tone	Tone	13.42 ± 70.77	−64.74 ± 66.7	
(7) Involuntary Action - Tone	Involuntary Action	73.68 ± 59.55	−8.95 ± 43.48	211.05 ± 90.79
(8) Involuntary Action - Tone	Tone	30.26 ± 60.72	−47.89 ± 59.82	
(9) Control Tone - Tone	Control Tone	79.21 ± 34.65	−2.37 ± 51.22	209.74 ± 70.79
(10) Control Tone - Tone	Tone	35.53 ± 53.98	−42.63 ± 50.2	

Table 4
mJEs, perceptual shifts and overall binding in elderly people.

	Event Judged	mJE (ms) ± sd	Mean Shift (ms) ± sd	Mean Overall Binding (ms) ± sd
Baseline Conditions				
(1) Voluntary Action	Voluntary Action	−21.11 ± 91.37		
(2) Involuntary Action	Involuntary Action	45.83 ± 61.91		
(3) Tone	Tone	8.33 ± 56.12		
(4) Control Tone	Control Tone	27.5 ± 58.04		
Experimental Conditions				
(5) Voluntary Action - Tone	Voluntary Action	23.06 ± 116.75	44.17 ± 94.19	166.39 ± 140.12
(6) Voluntary Action - Tone	Tone	−31.11 ± 80.08	−39.44 ± 79.26	
(7) Involuntary Action - Tone	Involuntary Action	48.33 ± 57.03	2.5 ± 39.34	158.89 ± 83.85
(8) Involuntary Action - Tone	Tone	−80.28 ± 70.95	−88.61 ± 60.14	
(9) Control Tone - Tone	Control Tone	13.33 ± 56.33	−14.17 ± 34.22	194.17 ± 91.22
(10) Control Tone - Tone	Tone	−61.67 ± 72.11	−70 ± 77.04	

$\eta_p^2 = 0.114$, (Fig. 5). The young adults overall binding significantly differed from both the children ($p = 0.015$) and the elderly ($p = 0.022$) only in the case of the 'voluntary action context'. Total voluntary IB did not differ between children and elderly ($p = 1.000$). No differences emerged among groups with regard to the two control contexts (involuntary action context: children vs young adults, $p = 1.000$; children vs elderly, $p = 0.293$; young adults vs elderly: $p = 1.000$; sensory context: children vs young adults, $p = 1.000$; children vs elderly, $p = 1.000$; young adults vs elderly: $p = 1.000$).

To determine if changes in IB could be associated with cognitive abilities, non-parametric correlations were run. However, no significant results emerged (all $p_s > 0.05$). We also explored how IB was processed within each single group. Regarding *young adults*, a significant interaction between 'type of context' and 'judged event' was found, $F(2,38) = 21.37$, $p < 0.001$; $\eta_p^2 = 0.529$. Concerning the first judged event (i.e., the shift of the first event towards the second one), a significant difference was found for voluntary action in comparison with involuntary action ($p < 0.001$) and control tone ($p < 0.001$). Involuntary action and control tone were not significantly different ($p = 0.178$). Significant differences also emerged when the second event (e.g., tone) ('voluntary action context' vs 'involuntary action context', $p = 0.034$; 'voluntary action context' vs 'sensory context', $p = 0.003$) was compared. The tone following the involuntary action was not significantly different to that following the control tone ($p = 1.000$). The interaction occurred because voluntary actions led to a perceptual shift of action towards tone and vice versa, whereas this effect was significantly reduced for the involuntary action and sensory contexts. In addition, the repeated-measures ANOVA detected a

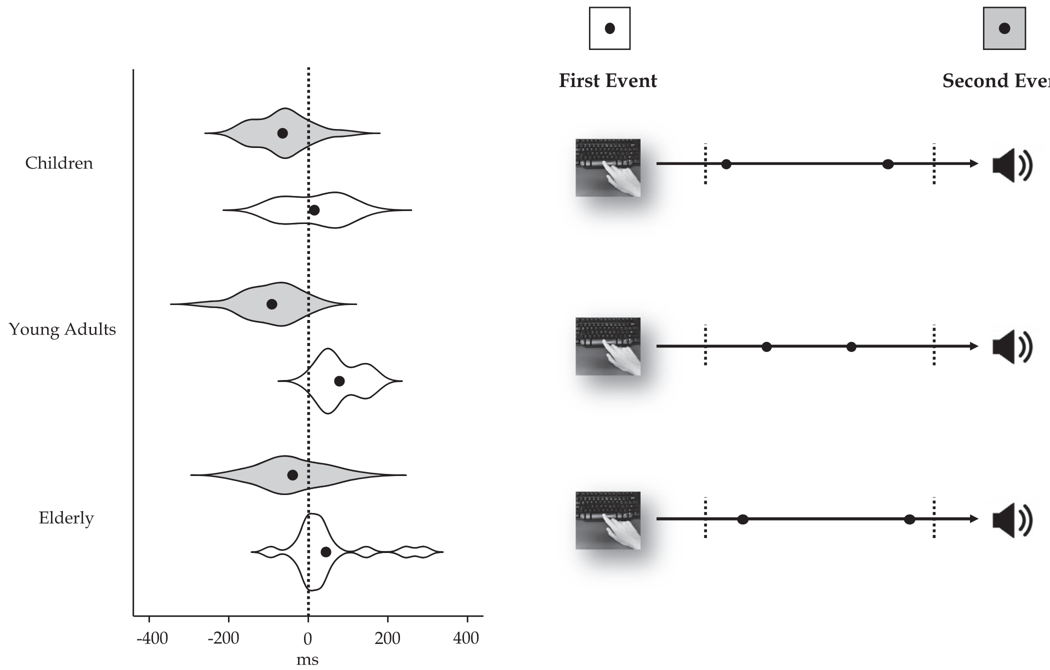

Fig. 4. On the **left**, the graph shows the perceptual shifts within the voluntary action context for each group. The white violin plots depict the action binding (i.e., the shift of the voluntary action towards the tone). Conversely, the grey violin plots represent the effect binding (i.e., the perceptual shift of the tone towards the action). The dashed line stands for the actual onset of the event of interest. The black dots stand for the mJE of each group of participants. On the **right**, a schematic, graphical and symmetrical representation is depicted. Again, the dashed lines stand for the actual onset of the event of interest, while the black dots represent the perceived event by the participants. As the image depicts, the total temporal compression is evident only in the group of young adults.

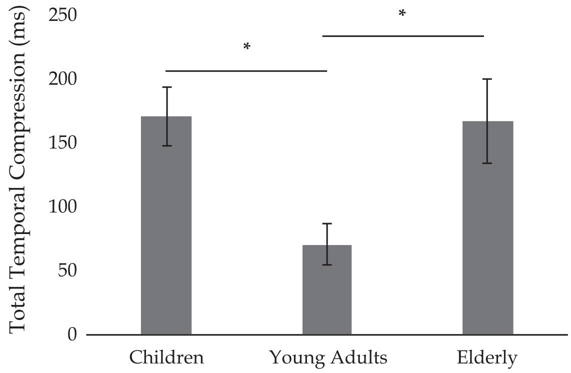

Fig. 5. Differences in the voluntary action overall binding among the three groups of participants. Error bars represent the standard error of mean (SEM) and * indicates the significant difference in overall binding among groups. Only adults present IB effect, showing an enhanced total temporal compression between voluntary action and its sensory effect. Small values indicate a stronger IB.

significant effect of the overall binding (i.e., the perceived linkage between action and effect), $F(2,38) = 17.42$, $p < 0.001$, $\eta_p^2 = 0.478$. *Post-hoc* comparisons showed a significant difference in both the voluntary and involuntary contexts ($p < 0.001$). In addition, the 'voluntary context' and the 'sensory context' ($p < 0.001$) were also significantly different. No significant differences were observed between the 'involuntary context' and the 'sensory context' ($p = 1.000$). In summary, temporal compression (i.e., the IB effect) was only evident in the context of voluntary action. The overall binding data indicate that the participants perceived the interval between their action and its effect as significantly shorter than it actually was although no direct judgment of the time interval's duration was requested. Overall, our results demonstrated that, when participants were actively causing the beep (i.e., tone), which was always presented 250 ms after their voluntary action, the onset of the voluntary action was perceived as occurring later, as if the action was 'attracted' towards the tone. Analogously, the tone onset was perceived as 'bound' to its voluntary action. This temporal compression phenomenon was only present with regard to voluntary action; when the beep followed an involuntary action or another control beep, that compression did not occur. Regarding *children*, we first compared the mJE of each event in the BC with the mJE of the same event in the EC using paired-samples *t*-tests. Significant differences were only detected in the perception of the tone in the ECs compared to the BCs, in which the tone was presented alone. These differences were not, however, limited to the cases of the voluntary action, $t_{18} = 4.23$, $p = 0.001$; they also extended to the two control conditions: involuntary action context, $t_{18} = 3.40$, $p = 0.003$, and sensory context, $t_{18} = 3.7$, $p = 0.002$. The tone (i.e., the effect/beep) was therefore perceived earlier when it followed the voluntary action, the involuntary action and the control tone, as compared to the BC. The perceptual shifts were also analysed in order to investigate IB. The repeated-measures ANOVA showed no significant interaction between the 'type of context' and the 'judged event', $F(2,36) = 1.39$, $p = 0.26$, $\eta_p^2 = 0.072$, indicating that no temporal compression occurred for the voluntary action as compared to the other control conditions. When considering the overall binding, no differences were observed among the three contexts ('voluntary action', 'involuntary action' and the 'sensory context'), $F(2,36) = 1.39$, $p = 0.26$, $\eta_p^2 = 0.072$. The results showed that no IB was present in the 10-year-old children. Just as for children, we compared the mJE of each event in the BC with the mJE of the same event in the EC in *elderly people*. Again, significant differences were only found in the perception of the tone in the ECs compared to the BCs. These differences were not limited to the voluntary action, $t_{17} = 2.11$, $p = 0.05$; they also extended to the two control conditions: involuntary action, $t_{17} = 6.25$, $p < 0.001$, and control tone, $t_{17} = 3.86$, $p = 0.001$. The tone was therefore perceived earlier when it followed the voluntary action, the involuntary action, or control tone, as compared to the BC where only the tone was presented. Perceptual shifts were also analysed in order to investigate IB. The repeated-measures ANOVA showed no significant interaction between the two factors 'type of context' and 'judged event', $F(2,34) = 0.63$, $p = 0.538$, $\eta_p^2 = 0.036$, indicating that no temporal compression occurred for the voluntary action as compared to the other two control conditions. With regard to the overall binding, no differences were observed among the three contexts ('voluntary action', 'involuntary action' and the 'sensory' contexts), $F(2,34) = 0.63$, $p = 0.54$, $\eta_p^2 = 0.036$. Just as with the children, the results showed that no IB occurred in elderly people.

4. Discussion

The aim of this study was to investigate the development of SoAg across the lifespan, using IB as an implicit measure (Haggard et al., 2002). Our results showed that only young adults showed temporal compression characteristic of voluntary actions. These findings are in line with previous studies (e.g., Barlas & Obhi, 2013; Cavazzana et al., 2014, 2015; Haggard & Clark, 2003; Haggard et al., 2002; Khalighinejad et al., 2016; Moore & Haggard, 2008) and confirm the application of our paradigm as a reliable implicit measure to study agency, especially when testing SoAg in special populations, like those included in the present study (i.e., children and elderly people). Although the Libet clock methodology has been successfully used in a large number of studies investigating IB (for a review, see: Moore & Obhi, 2012), the paradigm is not without its limitations (e.g., Pockett & Miller, 2007). Although a discussion on methodological issues concerned with the paradigm goes beyond the scope of this study, the most important limitation which disuaded us from its use was the use of a clock to report time when testing children and elderly people. It is indeed known that the acquisition of both clock and time knowledge changes with age (Vakali, 1991), tapping into a wide range of cognitive abilities, including EFs (Shulman, 2000). For this reason, the clock method was far from being the best choice for the present study.

Children and elderly people showed a reduction in the overall IB (i.e., larger values and absence of temporal compression), both in the context of 'voluntary action' and in the two control conditions ('involuntary action' and 'sensory context'). In both groups, the temporal occurrence of the tone in the ECs was significantly shifted towards the first event triggering the auditory effect, independently of the type of the first stimulus (i.e., voluntary, involuntary or sensory). Potential explanations for these results are diverse. A possible interpretation for the elderly group considers the *alerting system* (Petersen & Posner, 2012), which refers to the ability to actively prepare for an expected event allowing for a more rapid and accurate response. Generally, reaction times improve following a warning signal. A similar phenomenon (i.e., the 'warning-signal hypothesis'; Droit-Volet, 2003, 2011) is also common in children and has been thoroughly discussed in previous work from our group (Cavazzana et al., 2014) and seems to represent a suitable explanation for the present results. Accordingly, when target stimuli are preceded by warning signals, the amount of time required for stimulus processing decreases and accuracy improves. In our case, children are indeed more accurate in judging the second event in the ECs compared to the BCs, in which only one event is presented at random latencies. However, when considering the elderly group, the *alerting system* framework failed to provide a convincing explanation for the obtained findings. This could be partially due to the fact that the baseline temporal perception of the tone significantly differed between the two groups. More specifically, while children had a delayed temporal perception of the tone in BC (78.15 ms), elderly people tended to be more accurate (8.33 ms). As seen before, the *alerting system hypothesis* seems to work in children since the values of the tone in ECs were more accurate with respect to the BCs. However, in the older participants the first event could not be considered as a warning stimulus since in ECs the temporal perception of the second event (i.e., the tone) was less accurate with respect to the BC, although it was perceived earlier in time like in children. This is in line with other studies that demonstrated that older participants are unable to use temporal cues to improve performance (Vallesi, McIntosh, & Stuss, 2009; Zanto et al., 2011).

Another possible explanation could be found in a *lack of inhibitory control*, which seems to provide a valuable explanation for both children (Diamond & Doar, 1989; Durston et al., 2002; Lorsbach & Reimer, 2011; Rubia et al., 2000) and elderly people's data (Hasher, Zacks, & May, 1999). In the present study, both the children and elderly group might have perceived the second event in the ECs earlier in time, with respect to the BCs, because they may have been influenced by the presence of the first event. In fact, when the tone is triggered by the first event (voluntary action, involuntary action, or control tone) in the ECs, it is perceived earlier with respect to the BCs. In other words, when the children and the elderly people had to evaluate the second event in the ECs, it is likely that they were unable to disengage their attention from the irrelevant stimulus (i.e., the first event), which was therefore not well-inhibited. For this reason, the second event in the ECs was perceived earlier with respect to the BCs. Regarding children, this hypothesis finds support in other studies (Diamond & Doar, 1989; Durston et al., 2002; Lorsbach & Reimer, 2011; Rubia et al., 2000), suggesting that the loss of inhibitory skills could be the substrate for cognitive decline across the lifespan (Hasher et al., 1999). More specifically, older adults find difficult to focus on relevant information and, at the same time, to inhibit attention to irrelevant contents. Aging has resulted in poorer performance in a variety of paradigms relying upon inhibitory processing, including stop signal tasks (Kramer, Humphrey, Larish, Logan, & Strayer, 1994), the Stroop task (Houx, Jolles, & Vreeling, 1993) and antisaccade tasks (Butler, Zacks, & Henderson, 1999). The hypothesis of a *lack of inhibitory control* could provide a good framework to explain the shift of the tone towards the first event in both groups. In addition, with respect to children, the hypothesis of a lack of inhibitory control could better fit the data obtained with respect to the 'warning signal hypothesis' (Droit-Volet, 2003, 2011): in fact, in order to control the cross-modal estimations in timing judgments, we should consider the perceptual shifts and not just the difference between the BCs and the ECs. The second event seems to be influenced by the first one: the effect (e.g., tone) is perceived earlier towards the first event independently of the context, and the shift is numerically different between the first and the second event, with a greater shift for the second one. It is, therefore, more likely that the children, like elderly people, were unable to manage the interference caused by the first event and, consequently, to correctly evaluate the ensuing tone. Indeed, judging correctly the second event implies that attention is disengaged from the previously presented stimulus (i.e., the first event). In these cases, irrelevant information consumed resources that would otherwise have been available to process relevant information, and led to global decline in performance.

In order to better characterize the result of a reduced IB in these two special populations, we compared their data with those obtained in young adults. This analysis helped to resolve the possible issue concerning a lack of IB exclusively due to the complexity of the task. If that was the case, differences within all the three contexts (i.e., voluntary, involuntary and sensory ones) should have been observed. More precisely, both children and elderly should have differentiated from young adults in all three contexts. The groups did not differ in terms of control conditions; rather, they only showed significant differences in the 'voluntary action' context, suggesting that the total temporal compression characterizes adults only (Fig. 5). On the other hand, when considering action and effect binding separately, children exhibited a reduced action binding (i.e., the shift of the action towards the tone) only when compared to the adults (Fig. 4). Children tended to be more focused on their voluntary actions, without taking into account the effects produced by them. This result might be explained by considering the two different processes implicated in action and effect binding (Moore, Schneider et al., 2010; Wolpe, Haggard, Siebner, & Rowe, 2013). Effect binding seems to rely on a more general pre-activation mechanism (Waszak, Cardoso-Leite, & Hughes, 2012); the neural representation of a sensory outcome following a voluntary action is activated before its occurrence. When the predicted sensory event occurs, the perceptual threshold is reached faster than when the event is not predicted. On the other hand, action binding depends on both predictive motor control and inferential processes (Moore & Haggard, 2008). It is possible that a pre-activation mechanism is already fully efficient in children, while mechanisms implicated in action binding might still be developing, although functioning in elderly people. However, future studies are needed to shed light on this issue.

These data are also in line with literature regarding temporal perception. In adults, IB has been proven to be linked to the slowing of the rate of an internal pacemaker (Wenke & Haggard, 2009), while in children and in older participants this mechanism seems to accelerate (Droit-Volet & Wearden, 2002; Espinosa-Fernández, Miró, Cano, & Buela-Casal, 2003; Hancock & Rausch, 2010). In line with these findings, the increase in the speed of an internal pacemaker could have made children and elderly perceive their voluntary actions and their sensory effects to be further apart (i.e., a reduced IB).

5. Conclusions

In conclusion, this study provides new insights into the evolution of SoAg across the lifespan. It is possible that children and elderly people show a decreased IB effect because the frontal areas, the most plausible 'candidates' as a neural substrate of SoAg (e.g., Cavazzana et al., 2015; Haggard, 2017; Moore, Ruge et al., 2010), are still developing or have started to loose their efficiency. For all of these reasons, it has been suggested that IB might be acquired gradually during ontogenesis, parallel with the maturation of the frontal cortical network, and might be lost with advancing age. However, the hypothesis of a link between the reduced IB and the maturation or decline of frontal areas in children and elderly people remains an open issue that needs to be tested by means of neuroimaging techniques. Finally, these data could be important when considered in light of some legal aspects: our society condemns behaviours with negative consequences on the external world or on other people. However, some populations, like those tested in the present study, seem to exhibit a lack of agency, suggesting the possibility that a different 'route of judgment' could arise, as compared to adults.

Acknowledgments

This study was partially supported by a grant from the Bial Foundation (84/12 to P.S.B).

References

Aarts, H., Custers, R., & Marien, H. (2009). Priming and authorship ascription: When nonconscious goals turn into conscious experiences of self-agency. *Journal of Personality and Social Psychology*, *96*(5), 967.

Allen, E. A., Erhardt, E. B., & Calhoun, V. D. (2012). Data visualization in the neurosciences: Overcoming the curse of dimensionality. *Neuron*, *74*(4), 603–608.

Appollonio, I., Leone, M., Isella, V., Piamarta, F., Consoli, T., Villa, M. L., ... Nichelli, P. (2005). The Frontal Assessment Battery (FAB): Normative values in an Italian population sample. *Neurological Sciences*, *26*(2), 108–116.

Barlas, Z., & Obhi, S. S. (2013). Freedom, choice, and the sense of agency. *Frontiers in Human Neuroscience*, *7*.

Biancardi, A., & Stoppa, E. (1997). Il test delle Campanelle Modificato: Una proposta per lo studio dell'attenzione in età evolutiva. *Psichiatria dell'infanzia e dell'adolescenza*, *64*, 73–84.

Butler, K. M., Zacks, R. T., & Henderson, J. M. (1999). Suppression of reflexive saccades in younger and older adults: Age comparisons on an antisaccade task. *Memory & Cognition*, *27*(4), 584–591.

Casey, B. J., Tottenham, N., Liston, C., & Durston, S. (2005). Imaging the developing brain: What have we learned about cognitive development? *Trends in Cognitive Sciences*, *9*(3), 104–110.

Cavazzana, A., Begliomini, C., & Bisiacchi, P. S. (2014). Intentional binding effect in children: Insights from a new paradigm. *Sense of Agency: Examining Awareness of the Acting Self*.

Cavazzana, A., Penolazzi, B., Begliomini, C., & Bisiacchi, P. S. (2015). Neural underpinnings of the 'agent brain': New evidence from transcranial direct current stimulation. *European Journal of Neuroscience*, *42*(3), 1889–1894.

Daprati, E., Franck, N., Georgieff, N., Proust, J., Pacherie, E., Dalery, J., & Jeannerod, M. (1997). Looking for the agent: An investigation into consciousness of action and self-consciousness in schizophrenic patients. *Cognition*, *65*(1), 71–86.

Diamond, A., & Doar, B. (1989). The performance of human infants on a measure of frontal cortex function, the delayed response task. *Developmental Psychobiology*, *22*(3), 271–294.

Droit-Volet, S. (2003). Alerting attention and time perception in children. *Journal of Experimental Child Psychology*, *85*(4), 372–384.

Droit-Volet, S. (2011). Child and time. In A. Vatakis, A. Esposito, M. Giagkou, F. Cummins, & G. Papdelis (Eds.), *Multidisciplinary aspects of time and time perception* (pp. 151–173). Berlin Heidelberg: Springer-Verlag.

Droit-Volet, S., & Wearden, J. (2002). Speeding up an internal clock in children? Effects of visual flicker on subjective duration. *The Quarterly Journal of Experimental Psychology: Section B*, *55*(3), 193–211.

Durston, S., Thomas, K. M., Yang, Y., Ulug, A. M., Zimmerman, R. D., & Casey, B. J. (2002). A neural basis for the development of inhibitory control. *Developmental Science*, *5* F9–F9.

Espinosa-Fernández, L., Miró, E., Cano, M., & Buela-Casal, G. (2003). Age-related changes and gender differences in time estimation. *Acta Psychologica*, *112*(3), 221–232.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189–198.

Frith, C. D. (2014). Action, agency and responsibility. *Neuropsychologia*, *55*, 137–142.

Gallagher, S. (2000). Philosophical conceptions of the self: implications for cognitive science. *Trends in Cognitive Sciences*, *4*(1), 14–21.

Gawronski, B., LeBel, E. P., & Peters, K. R. (2007). What do implicit measures tell us?: Scrutinizing the validity of three common assumptions. *Perspectives on Psychological Science*, *2*(2), 181–193.

Haggard, P. (2017). Sense of agency in the human brain. *Nature Reviews Neuroscience*, *18*(4), 196–207.

Haggard, P., & Chambon, V. (2012). Sense of agency. *Current Biology*, *22*(10), R390–R392.

Haggard, P., & Clark, S. (2003). Intentional action: Conscious experience and neural prediction. *Consciousness and Cognition*, *12*(4), 695–707.

Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience*, *5*(4), 382–385.

Haggard, P., Martin, F., Taylor-Clarke, M., Jeannerod, M., & Franck, N. (2003). Awareness of action in schizophrenia. *NeuroReport*, *14*(7), 1081–1085.

Haggard, P., & Tsakiris, M. (2009). The experience of agency feelings, judgments, and responsibility. *Current Directions in Psychological Science*, *18*(4), 242–246.

Hancock, P. A., & Rausch, R. (2010). The effects of sex, age, and interval duration on the perception of time. *Acta Psychologica*, *133*(2), 170–179.

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher, & A. Koriat (Eds.), *Attention and performance XVII, cognitive regulation of performance. Interaction of theory and application* (pp. 653–675). Cambridge, MA: The MIT Press.

Houx, P. J., Jolles, J., & Vreeling, F. W. (1993). Stroop interference: aging effects assessed with the Stroop Color-Word Test. *Experimental Aging Research*, *19*(3), 209–224.

Khalighinejad, N., Di Costa, S., & Haggard, P. (2016). Endogenous action selection processes in dorsolateral prefrontal cortex contribute to sense of agency: A meta-analysis of tDCS studies of 'intentional binding'. *Brain Stimulation*.

Khalighinejad, N., & Haggard, P. (2015). Modulating human sense of agency with non-invasive brain stimulation. *Cortex*.
Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition. *Psychology and Aging*, *9*(4), 491–512.
Kühn, S., Brass, M., & Haggard, P. (2013). Feeling in control: Neural correlates of experience of agency. *Cortex*, *49*(7), 1935–1942.
Lorsbach, T. C., & Reimer, J. F. (2011). Developmental differences in the use of task goals in a cued version of the stroop task. *British Journal of Developmental Psychology*, *29*(1), 138–147.
Metcalfe, J., Eich, T. S., & Castel, A. D. (2010). Metacognition of agency across the lifespan. *Cognition*, *116*(2), 267–282.
Metcalfe, J., & Greene, M. J. (2007). Metacognition of agency. *Journal of Experimental Psychology: General*, *136*(2), 184.
Moll, J., Oliveira-Souza, R. D., Garrido, G. J., Bramati, I. E., Caparelli-Daquer, E. M., Paiva, M. L., ... Grafman, J. (2007). The self as a moral agent: Linking the neural bases of social agency and moral sensitivity. *Social Neuroscience*, *2*(3–4), 336–352.
Mondini, S., Mapelli, D., Vestry, A., Arcara, G., & Bisiacchi, P. S. (2011). *Esame neuropsicologico breve 2*. Milano: Raffaello Cortina.
Moore, J. W. (2016). What is the sense of agency and why does it matter? *Frontiers in Psychology*, *7*.
Moore, J., & Haggard, P. (2008). Awareness of action: Inference and prediction. *Consciousness and Cognition*, *17*(1), 136–144.
Moore, J. W., & Obhi, S. S. (2012). Intentional binding and the sense of agency: A review. *Consciousness and Cognition*, *21*(1), 546–561.
Moore, J. W., Ruge, D., Wenke, D., Rothwell, J., & Haggard, P. (2010). Disrupting the experience of control in the human brain: Pre-supplementary motor area contributes to the sense of agency. *Proceedings of the Royal Society of London B: Biological Sciences* rspb20100404.
Moore, J. W., Schneider, S. A., Schwingenschuh, P., Moretto, G., Bhatia, K. P., & Haggard, P. (2010). Dopaminergic medication boosts action–effect binding in Parkinson's disease. *Neuropsychologia*, *48*(4), 1125–1132.
Moretto, G., Walsh, E., & Haggard, P. (2011). Experience of agency and sense of responsibility. *Consciousness and Cognition*, *20*(4), 1847–1854.
Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113.
Pacherie, E. (2008). The phenomenology of action: A conceptual framework. *Cognition*, *107*(1), 179–217.
Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, *35*, 73.
Pockett, S., & Miller, A. (2007). The rotating spot method of timing subjective events. *Consciousness and Cognition*, *16*(2), 241–254.
Pruneti, C. A., Fenu, A., Freschi, G., Rota, S., Cocci, D., & Marchionni, M. (1996). Update of the Italian standardization of the test of Raven Colored Progressive Matrices (CPM). *Bollettino di Psicologia Applicata*, *217*, 51–57.
Raz, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings.
Renes, R. A., van Haren, N. E., Aarts, H., & Vink, M. (2015). An exploratory fMRI study into inferences of self-agency. *Social Cognitive and Affective Neuroscience*, *10*(5), 708–712.
Renes, R. A., Vink, M., van der Weiden, A., Prikken, M., Koevoets, M. G., Kahn, R. S., ... van Haren, N. E. (2016). Impaired frontal processing during agency inferences in schizophrenia. *Psychiatry Research: Neuroimaging*, *248*, 134–141.
Rubia, K., Overmeyer, S., Taylor, E., Brammer, M., Williams, S. C. R., Simmons, A., ... Bullmore, E. T. (2000). Functional frontalisation with age: Mapping neurodevelopmental trajectories with fMRI. *Neuroscience & Biobehavioral Reviews*, *24*(1), 13–19.
Scarpa, P., Piazzini, A., Pesenti, G., Brovedani, P., Toraldo, A., Turner, K., ... Bottini, G. (2006). Italian neuropsychological instruments to assess memory, attention and frontal functions for developmental age. *Neurological Sciences*, *27*(6), 381–396.
Shulman, K. I. (2000). Clock-drawing: Is it the ideal cognitive screening test? *International Journal of Geriatric Psychiatry*, *15*(6), 548–561.
Stuss, D. T., & Levine, B. (2002). Adult clinical neuropsychology: Lessons from studies of the frontal lobes. *Annual Review of Psychology*, *53*(1), 401–433.
Vakali, M. (1991). Clock time in seven to ten year-old children. *European Journal of Psychology of Education*, *6*(3), 325–336.
Vallesi, A., McIntosh, A. R., & Stuss, D. T. (2009). Temporal preparation in aging: A functional MRI study. *Neuropsychologia*, *47*(13), 2876–2881.
van Elk, M., Rutjens, B. T., & van der Pligt, J. (2015). The development of the illusion of control and sense of agency in 7-to-12-year old children and adults. *Cognition*, *145*, 1–12.
Waszak, F., Cardoso-Leite, P., & Hughes, G. (2012). Action effect anticipation: Neurophysiological basis and functional consequences. *Neuroscience & Biobehavioral Reviews*, *36*(2), 943–959.
Wenke, D., & Haggard, P. (2009). How voluntary actions modulate time perception. *Experimental Brain Research*, *196*(3), 311–318.
West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, *120*(2), 272.
Wolpe, N., Haggard, P., Siebner, H. R., & Rowe, J. B. (2013). Cue integration and the perception of action in intentional binding. *Experimental Brain Research*, *229*(3), 467–474.
Wolpe, N., Moore, J. W., Rae, C. L., Rittman, T., Altena, E., Haggard, P., & Rowe, J. B. (2013). The medial frontal-prefrontal network for altered awareness and control of action in corticobasal syndrome. *Brain*, awt302.
Zanto, T. P., Pan, P., Liu, H., Bollinger, J., Nobre, A. C., & Gazzaley, A. (2011). Age-related changes in orienting attention in time. *The Journal of Neuroscience*, *31*(35), 12461–12470.
Zelazo, P. D., & Müller, U. (2002). Executive function in typical and atypical development.
Zelazo, P. D., Craik, F. I., & Booth, L. (2004). Executive function across the life span. *Acta Psychologica*, *115*(2), 167–183.