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Sequential modulations of executive control processes throughout lifespan in numerosity comparison

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A B S T R A C T

The present research aimed at determining (a) whether participants modulate executive control processes from one item to the next when they accomplish numerosity comparison tasks, and (b) how these modulations change across the lifespan. We tested sequential modulations of congruency effects in participants of different age groups. Sequential modulations of congruency effects refer to decreased congruency effects (i.e., poorer performance on incongruent items relative to congruent items) following incongruent items compared to after congruent items. Children (8-year-olds, 10-year-olds, and 13-year-olds), younger (18–30-year-olds) and older adults (65–94-year-olds) accomplished a dot comparison task. They were presented two collections of dots and had to decide which collection included the largest number of dots. Results showed that congruency effects were smaller on current items following incongruent items (i.e., visual feature mismatched numerosity) than after congruent items (i.e., visual feature matched numerosity) in 13-year-old-children, as well as in young and older adults. In 8-year-old-children, reverse sequential modulations of congruency effects were observed (i.e., congruency effects on current items increased following incongruent items), while congruency effects on current items were not different after congruent and incongruent items in 10-year-old-children. Finally, age-related differences in sequential modulations of congruency effects depend on efficiency of participants' executive control processes. These findings have important implications to further our understanding on how domain-general mechanisms contribute to numerosity comparison performance, and how such contribution changes across the lifespan.

1. Introduction

Numerosity comparison is a fundamental numerical skill that enables us to compare numerosities of two collections of items and to determine which one includes the largest number of items without counting them precisely. Several studies found that to compare numerosities of dot collections, participants rely on both domain-specific processes (numerosity) and domain-general processes (executive control; e.g., Barth et al., 2006; Dehaene, 1997; Gebuis & Reynvoet, 2011, 2012; Gilmore, Cragg, Hogan, & Inglis, 2016; Halberda & Feigenson, 2008). The present study brings evidence of domain-general processes which have not been documented in numerosity comparison tasks, namely sequential modulations of executive control processes, and shows how such processes change

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across the lifespan. Before outlining the logic of the present work, we first briefly review previous findings on numerosity comparison. Then, we discuss what is known about sequential modulations of executive control mechanisms in children, young, and older adults.

1.1. Previous findings on numerosity comparison

Numerosity estimation has been found in non-human animals and in humans, as well as in individuals of varying age groups, from infants to children to young and older adults (e.g., Barth et al., 2006; Cappelletti, Didino, Stoianov, & Zorzi, 2014; Clayton & Gilmore, 2015; Cordes, Gelman, Gallistel, & Whalen, 2001; Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004; Gebuis & Gevers, 2011; Gilmore et al., 2016; Halberda & Feigenson, 2008; Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011; Norris, McGeown, Guerrini, & Castronovo, 2015; Piazza et al., 2010; Pica, Lemer, Izard, & Dehaene, 2004; Xu & Spelke, 2000).

To investigate processes and representations involved in numerosity comparison, researchers have used several types of tasks, including the dot comparison task used in the present study. In dot comparison tasks, participants are presented two dot collections and have to determine the more numerous dot collections. Several factors have been found to crucially influence participants' performance in dot comparison tasks (see Leibovich, Katzin, Harel, & Henik, 2017, for a review). These include numerical (e.g., numerosity or number of dots included in a collection) and visual characteristics of collection of dots (e.g., convex hull which corresponds to the smallest contour around the dot collections), as well as method of stimulus presentation (i.e., paired, sequential, or intermixed presentations; Price, Palmer, Battista, & Ansari, 2012).

First, participants' speed and accuracy in dot comparison tasks depend on numerical features of dot collections (e.g., Barth, La Mont, Lipton, & Spelke, 2005; DeWind & Brannon, 2016; Halberda et al., 2008; Halberda & Feigenson, 2008; Hellgren, Halberda, Forsman, Ådén, & Libertus, 2013; Odic, Libertus, Feigenson, & Halberda, 2013; Smets, Gebuis, Defever, & Reynvoet, 2014; see Gilmore, Göbel, & Inglis, 2018, for a review). For instance, participants are faster and more accurate on smaller than on larger collections of dots (e.g., Clayton & Gilmore, 2015; Revkin, Piazza, Izard, Cohen, & Dehaene, 2008), as well as on collections with larger than with smaller differences/ratios (e.g., Ansari, Garcia, Lucas, Hamon, & Dhital, 2005). Such findings have been explained as resulting from functioning characteristics of an "Approximate Number System" (ANS; Dehaene, 1997, p. 5). According to the ANS theory, comparing collections of dots relies on retrieving approximate representations of numerosities from long-term memory. These representations vary according to a normal distribution with mean n and standard deviation wn, where w is the Weber fraction. Distributions of two numerosity representations are more precise for small than for larger numerosities and overlap less for larger-ratio collections than for small-ratio collections, leading participants to be faster at comparing smaller vs. larger numerosities and larger-ratio collections (i.e., 8 *vs.* 16 dots) than smaller-ratio collections (i.e., 8 *vs.* 10 dots).

Second, when participants compare dot collections, they are sensitive to visual features of dots. For instance, they are faster on collections with larger than with smaller convex hull (e.g., Clayton & Gilmore, 2015; Gilmore et al., 2016), or on collections of dots that occupy a larger area on a computer screen than on collections displayed with a smaller area (e.g., Gebuis & Reynvoet, 2012). Also, participants' performance may be influenced by variations in tasks environment. For instance, participants are more accurate when collections of dots are displayed for longer than for shorter durations (e.g., Gilmore et al., 2016; Inglis & Gilmore, 2013). They are also faster when they have to compare two dot collections separately displayed on a computer screen than when the two collections of dots are displayed in different colors but intermixed (e.g., Price et al., 2012).

In addition, when numerical and visual features mismatch, dot comparison tasks involve general cognitive mechanisms, like executive control processes. Executive control processes (also called Executive Functions or Cognitive Control) "refer to a family of top-down mental processes needed when you have to concentrate and pay attention, when going on automatic or relying on instinct or intuition would be ill-advised, insufficient, or impossible" (Diamond, 2013, p. 136). Core executive control processes include (Miyake et al., 2000) (a) inhibitory control (resisting habits, temptations, or distractions), (b) working memory (mentally holding and processing information), and (c) cognitive flexibility (adjusting to change).

In dot comparison tasks, evidence of inhibitory control comes from congruency effects (e.g., Barth et al., 2006; Cappelletti et al., 2014; Clayton & Gilmore, 2015; Clayton, Gilmore, & Inglis, 2015; Fush & McNeil, 2013; Gebuis & Reynvoet, 2012; Gilmore, Keeble, Richardson, & Cragg, 2015; 2013; 2016; Halberda et al., 2008; Inglis & Gilmore, 2014; Nys & Content, 2012). In congruency effects, participants obtain poorer performance on incongruent trials (i.e., when numerical and visual information mismatch, such as when a smaller collection of dots is displayed with a larger convex hull) than on congruent trials (i.e., when numerical and visual information match, such as when a smaller collection of dots is displayed with a smaller convex hull). In incongruent trials, participants have to inhibit the irrelevant (visual) information to focus on the relevant dimension (numerosity) of stimulus.

The congruency effects have been found in domain-general tasks, such as Simon, Flanker, and Stroop tasks (Eriksen, 1995; Hommel, 2011; MacLeod, 1991) and in domain-specific tasks, such as arithmetic problem solving and dot comparison tasks. The Simon, Flanker, and Stroop tasks are usually seen as domain-general because they involve domain-general processes (like executive control processes). As such, they are viewed as tapping, domain-general processes that support processing and learning on a broad level regardless of the type of information that needs to be processed. Moreover, the dot comparison task involves domain-general processes together with domain-specific processes that are specific to the domain such as language or numbers (e.g., number encoding, retrieval of numerosity representations in long-term memory).

Congruency effects have been found in children, young, and older adults (e.g., Cappelletti et al., 2014; Clayton & Gilmore, 2015; Gebuis & Reynvoet, 2012; Gilmore et al., 2013; 2016). For example, Clayton and Gilmore (2015) asked children aged between 7 and 9 years to accomplish a dot comparison task including congruent (e.g., a larger convex hull for a larger collection of dots) or incongruent items (e.g., a smaller convex hull for a larger collection of dots). Children were more accurate on congruent than on incongruent items (see also Barth et al., 2006; Gebuis, Kadosh, de Haan, & Henik, 2009; Gilmore et al., 2013; Nys & Content, 2012;

Rousselle & Noël, 2008, for similar results). In their study, Rousselle and Noël (2008) found that congruency effects may also depend on participants' age. They asked 3-, 4-, 5-, and 6-year-old-children to accomplish a dot comparison task and found that congruency effects tended to decrease after 4-year-olds, suggesting that efficiency of inhibitory processes involved in dot comparison tasks increase as children grow older.

Age-related differences in congruency effects have also been found during adulthood in two studies (Cappelletti et al., 2014; Norris et al., 2015). Cappelletti et al. (2014) asked young (19–36-year-olds) and older adults (60–75-year-olds) to compare collections of dots that included between 5 and 16 dots. They found congruency effects in older but not in young adults. Indeed, older adults were specifically impaired on incongruent items, those items for which it is necessary to inhibit the irrelevant stimulus dimension. Similarly, Norris et al. (2015) compared young (19–25-year-olds) and older (60–77-year-olds) participants' performance on congruent and incongruent items in a dot comparison task. In this task, participants saw sets of yellow and blue dots and had to judge which colored set is more numerous. As in Cappelletti et al.'s (2014) study, congruency effects were only observed in older adults. Both these studies accounted for age-related declines on incongruent items by assuming declined efficiency in inhibition mechanisms with age.

There is a consensus to assume that congruency effects in dot comparison tasks in both children and adults of different ages result from the same mechanisms enabling participants to inhibit the irrelevant visual dimension of stimulus (e.g., convex hull) to focus on the relevant numerosity dimension (e.g., Clayton & Gilmore, 2015; Cappelletti et al., 2014; Gilmore et al., 2016; Norris et al., 2015). Unknown is whether participants sequentially (i.e., from one trial to the next) modulate these executive (inhibition) processes, which is what we aimed at determining in the present study. This possibility is based on previous findings on such sequential modulations outside numerosity comparison.

1.2. *Previous findings on sequential modulations of congruency effects (SMCE)*

In conflict tasks, like Stroop, Flanker, or Simon tasks, congruency effects on current items are modulated by the congruency of the immediately preceding items. Thus, congruency effects on current items are smaller following incongruent items than after congruent items (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Egner, Delano, & Hirsch, 2007; Gratton, Coles, & Donchin, 1992; Kerns et al., 2004; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Ullsperger, Bylsma, & Botvinick, 2005; see Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014, for a review). Such SMCE result from participants responding faster on current incongruent items following incongruent items relative to after congruent items. This phenomenon has been discussed in the dual mechanisms framework (Braver, Paxton, Locke, & Barch, 2009; Braver, Gray, & Burgess, 2007; see Braver, 2012, for a review) that distinguishes proactive and reactive modes of control (see also, Bugg & Crump, 2012). In proactive control, goal-relevant information is actively maintained in preparation for the occurrence of subsequent conflicting events, allowing efficient conflict processing after the processing of an incongruent item. Reactive control consists in the detection and resolution of an interference after the encoding of a conflicting event, enabling the recruitment of additional control mechanisms when participants did not prepare themselves to process a conflict.

SMCE have been investigated in children, young, and older adults with conflict tasks. Many authors reported sequential modulations from 7 years onwards (Huizinga & van der Molen, 2011; Iani, Stella, & Rubichi, 2014; Larson, Clawson, Clayson, & South, 2012; Nieuwenhuis et al., 2006; Stins, Polderman, Boomsma, & de Geus, 2007; Wilk & Morton, 2012) using different conflict tasks (e.g., Simon, Flanker, and/or Stroop tasks). In Kray, Karbach, and Blaye's (2012) study, SMCE were less present in 4–6-year-old-children than in 6–9-year-old-children, suggesting that proactive and reactive modes of control take place progressively during child development (see also Ambrosi, Lemaire, & Blaye, 2016; Chatham, Frank, & Munakata, 2009; Chevalier, 2015; Chevalier, James, Wiebe, Nelson, & Espy, 2014; Chevalier, Martis, Curran, & Munakata, 2015; Lucenet & Blaye, 2014).

Several studies have been conducted in older adults (i.e., after 63 years old) to test age-related diff ;erences in SMCE. Indeed, whereas Monti, Weintraub, and Egner (2010) showed age-related decrease in SMCE from one trial to the next (e.g., Lucci, Berchicci, Spinelli, Taddei, & Russo, 2013; Monti et al., 2010; Nessler, Friedman, Johnson, & Bersick, 2007), a number of studies reported age-related invariance in sequential modulations (e.g., Joyce, Smyth, Donnelly, & Davranche, 2014; Larson et al., 2016; Puccioni & Vallesi, 2012; West & Moore, 2005). A possible source of such inconsistent findings, based on individual diff ;erences among older adults, is suggested by Lemaire and Hinault's (2014) findings on individual differences in SMCE. In their study of arithmetic strategies, Lemaire and Hinault asked young (19–24-year-olds) and older adults (71–84-year-olds) to accomplish a computational estimation task in which they had to estimate the product of multiplication problems, such as 46 × 72, without calculating the exact product (i.e., doing 50 × 70 to estimate 46 × 72). For each problem, participants were required to execute a cued strategy (i.e., two letters indicated whether the rounding down-up strategy "DU" or the rounding up-down strategy "UD" should be used). The cued strategy could be the better strategy (i.e., the strategy that yields the closest estimate to the correct product) or the poorer strategy (i.e., the strategy that did not yield the closest estimate to the correct product). For instance, the rounding up-down strategy to estimate 46 × 72 (e.g., doing 50 × 70) yields a better estimate than using the rounding down-up strategy (e.g., doing 40 × 80). First, the authors reported "strategy congruency effects" on current problems (i.e., longer response times and larger error rates when the cued strategy was a poorer strategy relative to a better strategy). Second, strategy congruency eff ;ects on a given problem were modulated by the strategy executed on the immediately preceding problems. Specifically, strategy congruency eff ;ects were smaller following the poorer strategy, than after the better strategy (see also Hinault, Badier, Baillet, & Lemaire, 2017; Hinault, Lemaire, & Phillips, 2016; Lemaire & Hinault, 2014; Uittenhove & Lemaire, 2012, 2013, for similar results).

More interestingly, Lemaire and Hinault (2014) found important individual diff ;erences in how sequential modulations of strategy congruency eff ;ects change during aging. Indeed, using the Simon task to obtain independent measures of executive control processes, they were able to distinguish two subgroups of older adults. Sequential modulations of strategy congruency eff ;ects were found in so-called "high-control" group as in young adults whereas reverse sequential modulations of strategy congruency eff ;ects were observed in "low-control" group. Moreover, these individual differences in older adults correlated with relative efficiency of executive control processes assessed with the Simon task. That is, older adults with highly efficient executive control processes were as able as young adults to sequentially modulate congruency effects, whereas older adults with less efficient executive control processes did not. Lemaire and Hinault suggested that contradictory findings regarding age-related differences in SMCE, previously reported in conflict tasks, could depend on the sample of participants. Indeed, in samples including mostly "low-control" older adults, age-related differences in SMCE would be present, in contrast to samples including mostly "high-control" older adults. This led us to test our participants in this study with a Simon task, to obtain a measure of efficiency of executive control processes independently of our target, dot comparison task.

Despite several inconsistencies, most of the studies revealed that both children and adults showed SMCE in conflict tasks and found age-related changes in SMCE during both childhood and adulthood. Unknown however is whether participants modulate executive control processes from one trial to the next while they accomplish dot comparison tasks, and whether such modulations change with participants' age. The present study was conducted to pursue these issues.

1.3. Overview of the present study

The first objective of this study was to bring evidence of a new type of domain-general processes during numerosity comparison tasks, namely sequential modulations of executive control processes. This contributes to further our understanding of the set of cognitive processes that participants use to accomplish numerosity comparison tasks. The second objective was to examine age-related changes in these mechanisms during childhood and adulthood. Children, young, and older adults were asked here to compare briefly presented collections of dots and to say as quickly as possible which collection includes the largest number of dots. In Experiment 1, we tested children as young as 8-year-old, as previous studies testing children with conflict tasks found that children aged 7 or older are able to sequentially modulate congruency effects in these tasks (e.g., Ambrosi et al., 2016; Clayton & Gilmore, 2015; Iani et al., 2014; Larson et al., 2012; Nieuwenhuis et al., 2006; Stins et al., 2007; Wilk & Morton, 2012). We also tested two groups of older children in order to examine age-related changes in SMCE during dot comparison. In Experiment 2, we compared young and older adults to determine whether SMCE change during adulthood and whether such age-related changes depend on individual differences in efficiency of executive control processes.

Two hypotheses were tested here. First, when they accomplish dot comparison tasks, participants sequentially modulate processing of congruency between numerosity and convex hull information. Second, such sequential modulations change with age during childhood and during adulthood. These hypotheses make the following main predictions. Performance differences between congruent and incongruent items should be smaller following incongruent items relative to after congruent items. This Congruency on Current Items x Congruency on Previous Items interaction should occur if participants prepare themselves to efficiently process current incongruent items after incongruent items, leading them to more quickly detect and resolve conflict between numerosity (the relevant dimension) and convex hull (the irrelevant dimension). The hypothesis that processes used to sequentially modulate congruency effects changes during childhood predicts an Age x Congruency on Previous Items x Congruency on Current Items interaction. This interaction was tested in 8—13-year-old-children in Experiment 1 and in young and older adults in Experiment 2. Following findings that proactive and reactive modes of control take place progressively during child development, we predicted increasing sequential modulations as a function of age in children. This would suggest that maturation of mode of control enabled children to be more efficient on modulating executive control processes from one trial to the next. The Age x Congruency on Previous Items x Congruency on Current Items interaction was predicted in adults if older adults do not sequentially modulate inhibition processes, in contrast to young adults. This would be seen if congruency effects are found in older adults on current items when current items follow both congruent and incongruent items. This scenario is possible if, due to decreased processing resources with age, older adults process each item independently and do not prepare themselves to process interference on current items following incongruent items. Note that older adults may sequentially modulate mechanisms responsible for inhibition processes, but less efficiently (or systematically) than young adults. This latter possibility predicts that differences in congruency effects on current items following congruent and incongruent items would be smaller in older than in young adults.

Our final goal was to understand mechanisms underlying SMCE in numerosity comparison tasks. As a first step in this direction, each individual took part in the Simon task (Simon & Small, 1969) to test relations between SMCE in the dot comparison task and in the Simon task. We used the Simon task for two reasons. First, the Simon task is one of the domain-general conflict tasks that has been largely used to investigate executive control processes, both on each trial and for item-to-item sequential modulations of these congruency effects (see Egner et al., 2007, for a review). Second, several studies have shown the relevance of the Simon task for assessing the efficiency of item-to-item modulations of congruency effects in the domain of arithmetic (Hinault et al., 2016; Lemaire & Hinault, 2014; Roquet, Hinault, Badier, & Lemaire, 2018).

2. Experiment 1

2.1. Method

2.1.1. Participants

We tested 96 children (age range = 8–13 years)[3] in Experiment 1. Children were divided into three groups: 32 second graders (i.e., 8-year-olds), 32 fourth graders (i.e., 10-year-olds), and 32 seventh graders (i.e., 13-year-olds; see Table 1 for participants'

[3] We chose to test children aged between 8 and 13 to determine potential age-related effects on the SMCE. Indeed, several studies found that SMCE processes are already effective at the age of 12 (Huizinga & van der Molen, 2011; Larson et al., 2012; Stins et al., 2007; Nieuwenhuis et al., 2006).

Table 1
Participants' characteristics.

	Children						Adults			
	8-year-olds		10-year-olds		13-year-olds		Young		Older	
Characteristics	M	SD	M	SD	M	SD	M	SD	M	SD
n	32	–	32	–	32	–	32	–	28	–
Males/females	12/20	–	14/18	–	23/9	–	12/20	–	8/20	–
Mean age	8	0.5	10	0.5	13	0.6	23	2.6	76	9.3
Years of formal education	2	–	4	–	7	–	15	1.2	14	4.2
MHVS	–	–	–	–	–	–	23	4.9	24	6.3
MMSE	–	–	–	–	–	–			29	1.5

Note. MHVS = French version of the Mill-Hill Vocabulary Scale (Deltour, 1993; Raven, 1951). MHVS consists of 33 items distributed across three pages. Each item was a target word followed by six proposed words, and the tasks consisted in identifying which word had the closest meaning to that of the target. MMSE = Mini Mental State Examination (Folstein et al., 1975). None of the older adults obtained MMSE score lower than 27; therefore, none were excluding.

characteristics). They were from French urban public schools. Informed consents were obtained from children's parents after a presentation of the experiment.

2.1.2. Stimuli

The stimuli were collections of black dots (i.e., dot size was 0.5 cm or 20 pixels in diameter; dot size represented 0.45 degree of visual angle) presented on a white background. Each item consisted of two collections presented side by side on a 15´´ laptop screen. Based on previous findings showing that convex hull is one of the most salient visual features that interfere with participants' numerosity comparison performance (e.g., Clayton et al., 2015; Dietrich, Huber, Moeller, & Klein, 2015; Gilmore et al., 2015; Inglis & Gilmore, 2014; Smets et al., 2014), we have chosen to manipulate this feature. For each collection, convex hull was either smaller (i.e., 7.9 cm or 300 pixels in diameter) or larger (i.e., 10.6 cm or 400 pixels in diameter). Moreover, dots were randomly distributed and were at least 0.6 cm (or 25 pixels) away from each other to avoid dots overlap. In addition, all collections of dots had similar configurations. The dot comparison task included a total of 288 experimental items divided into two matched blocks of 144 items each. In each item, one dot collection always represented 24 dots and the other 18, 20, 22, 26, 28, or 30 dots, resulting in three ratios to create three levels of difficulty (i.e., calculated by dividing the larger number of dots by the smaller one). A third of the collections each instantiated easy (i.e., ratio 1.3 with 24:18 or 24:30 dots), medium (i.e., ratio 1.2 with 24:20 or 24:28 dots), or difficult ratios (i.e., ratio 1.1 with 24:22 or 24:26 dots).

There were two types of items (see Fig. 1A and Fig. 1B for examples): Convex hull and numerosity matched on congruent items (i.e., collections with the larger number of dots were presented with a larger convex hull, and collections with the smaller number of dots were presented with a smaller convex hull) and mismatched on incongruent items (i.e., collections with the smaller number of dots were presented with a larger convex hull, and collections with the larger number of dots were presented with a smaller convex hull).

Four types of trials were tested depending on whether convex hull and numerosity matched on current and previous items: congruent – congruent trials (i.e., numerosity and convex hull matched on both current and previous items), congruent – incongruent trials (i.e., numerosity and convex hull matched on previous items and mismatched on current items), incongruent – congruent trials (i.e., numerosity and convex hull mismatched on previous items and matched on current items), and incongruent – incongruent trials (i.e., numerosity and convex hull mismatched on both current and previous items).

Participants were tested using a Simon task to assess their inhibition. The Simon task consisted of responding, as quickly and accurately as possible, by pressing on the appropriate response key (i.e., green or red) with the right or the left index finger, according to the figure displayed 7 cm either to the left or to the right of a central fixation point. Participants had to press on the red response key if a 2 cm × 3 cm blue rectangle was displayed and on the green response key if a 6 cm diameter blue circle was displayed. Participants practiced the Simon task on 20 items prior to the 120 experimental items. There were two types of items: 60 congruent items and 60 incongruent items. For congruent items, the spatial location of the stimulus corresponded to the task-relevant aspect of the stimulus (i.e., the circle was displayed on the left and the rectangle on the right sides of the screen). For incongruent items, the spatial location of the stimulus did not match with the task-relevant aspect of the stimulus (i.e., the circle was displayed on the right and the rectangle on the left sides of the screen).

2.1.3. Procedure and design

Participants were first individually tested in a dot comparison task. The presentation of stimuli was controlled by the E-Prime Software. Each item began with a 500-ms blank screen, followed by a warning signal ("*") displayed for 400-ms in the center of the screen. Then, each item was displayed for 2000-ms (Fig. 2). Participants were asked to indicate, as quickly and accurately as possible, which collection of dots included the largest number of dots by pressing on the appropriate response key (i.e., green or red) with the right or the left index finger. Participants were asked to respond within 2000-ms before stimulus disappears. If no response was given within 2000-ms, a blank screen appeared and participants had to press any key on the keyboard to move onto the next item.

In the Simon task, each item began with the presentation of a cross in the center of the computer screen that correspond to a fixation point. After 800-ms, one of the two stimuli was presented, and participants had to respond.

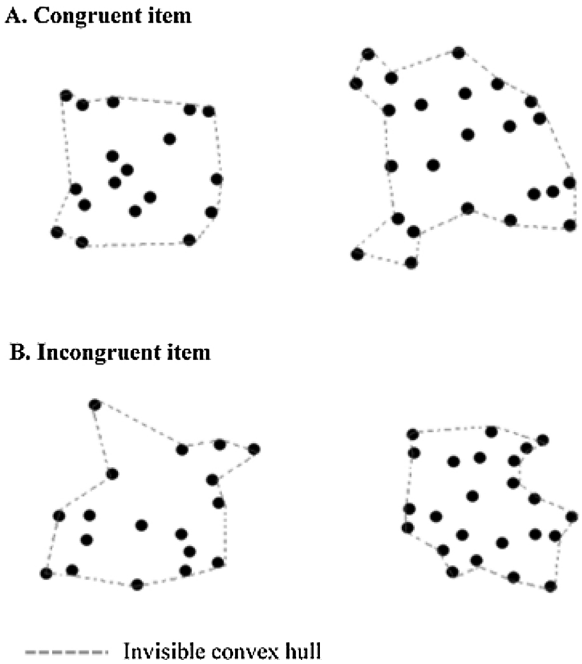


Fig. 1. Examples of (1A) a congruent item in which convex hull and numerosity matched (i.e., left collection contained 18 dots displayed with a smaller convex hull, and right collection included 24 dots displayed with a larger convex hull); (1B) an incongruent item in which convex hull and numerosity mismatched (i.e., left collection contained 18 dots displayed with a larger convex hull, and right collection included 24 dots displayed with a smaller convex hull).

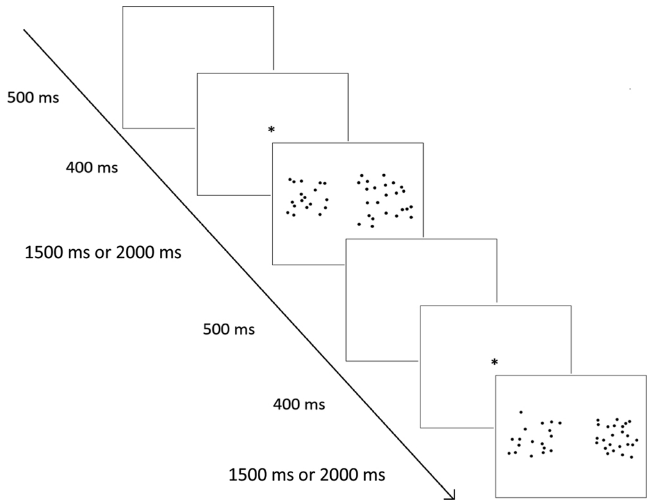


Fig. 2. Sequence of events in a trial. Stimuli were presented for 2000-ms to children and 1500-ms to young and older adults.

2.2. Results and discussion

Preliminary analyses[4] were run with the block (1st *vs*. 2nd half of the experiment) and item difficulty (i.e., easy, medium, and difficult items) factors. Results showed that children were faster during the second than during the first block. Moreover, children made more errors on medium than on difficult or easy items (i.e., 35 %, 33 %, and 29 % respectively; $F = 14.25$; $MSe = 66$; $n^2p = 0.13$, $p < .001$; see Appendix A). No other main or interaction effects involving these two factors came out significant.

[4] Response times smaller than 200-ms were deleted from the tasks prior to the analyses in Experiments 1 and 2.

2.2.1. Age-related changes in SMCE during childhood in the dot comparison task

Following previous studies (e.g., Lemaire & Hinault, 2014; Hinault et al., 2016; Hinault, Lemaire, & Touron, 2016; 2017; Roquet et al., 2018), to assess SMCE on current trials, we compared participants' performance on current congruent and incongruent items as a function of congruency of the immediately preceding items.[5]

2.2.1. a Response times. To examine SMCE and age-related differences therein, mean response times and error rates were analyzed using 3 (Age: 8-, 10-, and 13-year-olds) × 2 (Congruency on the previous items: Congruent, Incongruent) × 2 (Congruency on the current items: Congruent, Incongruent) mixed-design ANOVAs, with age as the only between-participants factor (see means in Table 2; see Appendix B for summary of statistical results).

Children were 60-ms faster on current congruent items than on current incongruent items ($F(1, 93) = 155.61$, $MSe = 2210$, $n^2p = .63$, $p < .001$). They sequentially modulated congruency effects, as shown by a significant interaction between congruency on the previous items and congruency on the current items ($F(1, 93) = 4.20$, $MSe = 3063$, $n^2p = .04$, $p < .05$). Most importantly, the Age × Congruency on the previous items × Congruency on the current items interaction was significant ($F(2, 93) = 9.45$, $MSe = 3063$, $n^2p = .17$, $p < .001$), showing that SMCE differed between groups. As shown in Fig. 3, congruency effects on current items were larger after incongruent items in 8- and 10-year-old-children, whereas they were smaller after incongruent items in 13-year-old-children. SMCE (i.e., congruency effects after congruent items – congruency effects after incongruent items) were found in 13-year-old-children (35 ms), whereas reverse SMCE were observed in 8- (−85 ms) and 10-year-old-children (−19 ms).

2.2.1. b Error rates. Analyses of errors revealed a main effect of age ($F(2, 93) = 12.07$, $MSe = 57$, $n^2p = .21$, $p < .001$). Pairwise comparisons revealed that 8-year-old-children made more errors than 10-year-old-children (41 % *vs.* 34 %; $p < .001$), or than 13-year-old-children (41 % *vs.* 31 %; $p < .001$). However, percentages of errors were similar in 10- (34 %) and 13-year-old-children (31 %). All children made more errors on current incongruent items (40 %) than on current congruent items (31 %; $F(1, 93) = 8.27$, $MSe = 985$, $n^2p = .08$, $p < .01$). Also, the significant Congruency on the previous items × Congruency on the current items interaction ($F(1, 93) = 18.62$, $MSe = 31$, $n^2p = .17$, $p < .001$) revealed larger congruency effects on current items following congruent items (12 %; $F(1, 93) = 13.37$, $n^2p = .13$, $p < .001$) than after incongruent items (7 %; $F(1, 93) = 4.17$, $n^2p = .04$, $p < .01$).

2.2.2. Age-related changes in SMCE during childhood in the Simon task

2.2.2. a Response times. Mean response times and percentages of errors on each item (Table 3) were analyzed using 3 (Age: 8-, 10-, and 13-year-old-children) × 2 (Congruency on the previous items: Congruent, Incongruent) × 2 (Congruency on the current items: Congruent, Incongruent) mixed-design ANOVAs, with age as the only between-participants factor (see Appendix C for summary of statistical results).

A main effect of age was found ($F(2, 93) = 47.22$, $MSe = 7824$, $n^2p = .50$, $p < .001$). Pairwise comparisons revealed that 13-year-old-children were faster than 10-year-old-children (523 ms *vs.* 611 ms; $p < .001$), or than 8-year-old-children (523 ms *vs.* 737 ms; $p < .001$). Also, 10-year-old-children were faster than 8-year-old-children (611 ms *vs.* 737 ms; $p < .001$). All children were 39-ms faster on current congruent items than on current incongruent items ($F(1, 93) = 64.89$, $MSe = 2265$, $n^2p = .41$, $p < .F001$). Most importantly, the Age × Congruency on the current items interaction was significant ($F(2, 93) = 6.61$, $MSe = 2265$, $n^2p = .12$, $p < .01$), showing that congruency effects on current items decreased as a function of age groups (23 ms, 31 ms, and 64 ms, respectively for 13-, 10-, and 8-year-old-children; $Fs > 7.25$).

Finally, the significant Congruency on the previous items × Congruency on the current items interaction ($F(2, 93) = 78.46$, $MSe = 1898$, $n^2p = .46$, $p < .001$, see Fig. 4) revealed larger congruency effects on current items following congruent items (79 ms; $F(1, 93) = 149.61$, $n^2p = .62$, $p < .001$) than after incongruent items (−0.26 ms; $F < 1$). Most importantly, SMCE were found in all age groups (i.e., 60 ms, 85 ms, and 91 ms, respectively in 8-, 10-, and 13-year-old-children), and there was no interaction between groups ($F < 1$).

2.2.2. b Error rates. Participants made fewer errors on current congruent (7 %) than on current incongruent items (13 %; $F(1, 93) = 44.14$, $MSe = 86$, $n^2p = .32$, $p < .001$). They made more errors following congruent items (11 %) than after incongruent items (9 %; $F(1, 93) = 9.76$, $MSe = 26$, $n^2p = .10$, $p < .01$). The Age × Congruency on the current items interaction was significant ($F(2, 93) = 3.18$, $MSe = 86$, $n^2p = .06$, $p < .05$), showing that congruency effects on current items decreased as a function of age groups (3 %, 7 %, and 9 %, respectively for 13-, 10-, and 8-year-old-children; $Fs > 3.85$). Also, the significant Congruency on the previous items ×x Congruency on the current items interaction ($F(1, 93) = 120.81$, $MSe = 41$, $n^2p = .57$, $p < .001$) revealed larger congruency effects on current items following congruent items (13 %; $F(1, 93) = 111.79$, $n^2p = .56$, $p < .001$) than after incongruent items (−0.9 %; $F < 1$).

Moreover, correlations between SMCE in both dot comparison and Simon tasks were conducted. SMCE for each child were calculated as the difference in congruency effects (i.e., mean response times for incongruent items – mean response times for

[5] We used four types of item sequences to calculate SMCE: Congruent – Congruent items; Congruent – Incongruent items; Incongruent – Congruent items; Incongruent – Incongruent items. Following previous studies (e.g., Lemaire & Hinault, 2014; Hinault et al., 2016, 2017; Roquet et al., 2018), to assess SMCE, we used the Incongruent – Congruent and the Congruent – Congruent item sequences. Thus, to assess performance after incongruent items, we calculated: [sequence (Incongruent – incongruent items) - sequence (Incongruent – Congruent items)]. To assess performance after congruent items, we calculated: [sequence (Congruent - Incongruent) – sequence (Congruent - Congruent)].

Table 2
Children' mean response times (in ms) and percentages of errors in the dot comparison task for current congruent and incongruent items following congruent or incongruent items (Standard Deviations in parentheses).

	8-year-olds			10-year-olds			13-year-olds		
	Congruency of previous items			Congruency of previous items			Congruency of previous items		
Congruency of current items	C	I	*Means*	C	I	*Means*	C	I	*Means*
	Mean response times (in ms)								
C	822 (126)	771 (139)	797 (133)	809 (148)	816 (156)	813 (152)	855 (135)	866 (137)	860 (136)
I	841 (163)	875 (116)	858 (139)	852 (160)	878 (155)	865 (157)	939 (160)	915 (140)	927 (150
CE	19	104***	61***	43**	62***	52***	84***	49***	67***
	Mean percentage of errors								
C	39 (21)	41 (20)	40 (20)	29 (14)	35 (15)	32 (15)	20 (12)	21 (13)	21 (12)
I	43 (15)	40 (17)	41 (16)	35 (15)	37 (15)	36 (15)	44 (16)	41 (17)	43 (16)
CE	4	−1	1	6	2	4	24***	20**	22***

Note. C = Congruent, I = Incongruent, *CE* = Congruency effects (Incongruent items – Congruent items).
*$p < .05$.
**$p < .01$.
***$p < .001$.

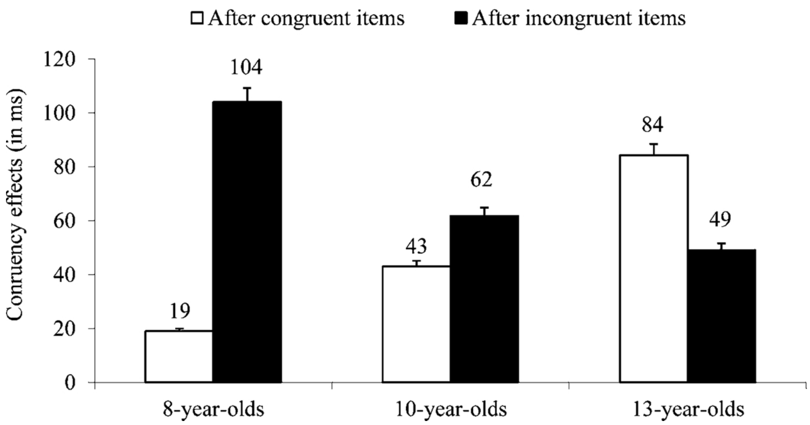


Fig. 3. SMCE (i.e., congruency effects on current items after congruent items – congruency effects on current items after incongruent items) in the dot comparison task for children. Error bars represent Confidence Intervals at 95 %.

Table 3
Children' mean response times (in ms) and percentages of errors in the Simon task for current congruent or incongruent items following congruent or incongruent items (Standard Deviation in parentheses).

	8-year-olds			10-year-olds			13-year-olds		
	Congruency of previous items			Congruency of previous items			Congruency of previous items		
Congruency of current items	C	I	*Means*	C	I	*Means*	C	I	*Means*
	Mean response times (in ms)								
C	692 (86)	718 (87)	705 (87)	571 (73)	620 (82)	595 (78)	485 (59)	539 (58)	512 (59)
I	786 (90)	751(79)	769 (85)	644 (81)	608 (72)	626 (76)	553 (54)	516 (57)	534 (55)
CE	94***	33*	64***	73***	−12	31***	68***	−23**	22***
	Mean percentage of errors								
C	6 (5)	10 (5)	8 (5)	4 (4)	9 (6)	7 (5)	3 (3)	10 (6)	7 (5)
I	22 (11)	13 (9)	17 (10)	17 (10)	9 (8)	13 (9)	14 (8)	5 (4)	11 (6)
CE	16***	3	9***	13***	0	5***	11***	−5	4**

Note. C = Congruent, I = Incongruent, *CE* = Congruency effects (Incongruent items – Congruent items).
* $p < .05$.
** $p < .01$.
*** $p < .001$.

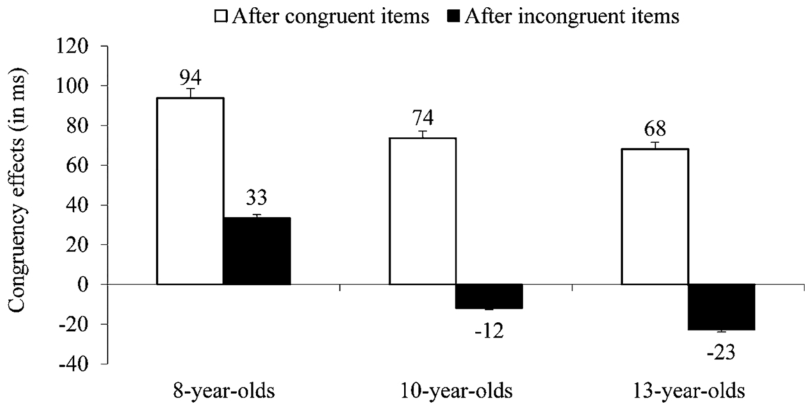


Fig. 4. SMCE (i.e., congruency effects on current items after congruent items – congruency effects on current items after incongruent items) in the Simon task for children. Error bars represent Confidence Intervals at 95 %.

congruent items) following congruent and incongruent items. No significant correlations were found in each age group.

In summary, SMCE in the dot comparison task were found in 13-year-old-children, an age at which executive control processes were efficient enough for such sequential modulations to occur. In 8-year-old-children, reverse SMCE were observed, such that congruency effects on current items increased following incongruent items. Finally, in 10-years-old-children, congruency effects on current items were not different after congruent and incongruent items.

SMCE in the Simon task were comparable in all groups of children. However, age-related differences were found on congruency effects. Indeed, congruency effects were larger in 8-year-old-children, than 10-year-old-children, or than 13-year-old-children.

3. Experiment 2

3.1. Method

3.1.1. Participants

We tested 32 young adults (age range = 18–30 years) and 28 older adults (age range = 65–94 years; see Table 1 for participants' characteristics) in Experiment 2. Young adults were undergraduates from Aix-Marseille University (Marseille, France), who voluntarily participated in this experiment. Older adults were recruited from the community of Marseille, with no cognitive or health-related problems. They all had scores larger than 27 in the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975). Moreover, both adult age groups completed a French version of the Mill-Hill Vocabulary Scale (MHVS; Deltour, 1993) to measure verbal intelligence (i.e., reproductive ability or acquired information). A one-way ANOVA on vocabulary scores in the two adult groups indicated no age-related differences ($F < 1$). Informed consents were obtained from adults after a presentation of the experiment.

3.1.2. Stimuli and procedure

As in Experiment 1, participants completed a similar dot comparison task. They had to select the more numerous collections by pressing on the appropriate response key (i.e., L or S) with the right or the left index finger. The procedure only differed in terms of the presentation time of the collections. Participants had to respond within 1500 ms before the stimulus disappears. Then, they were tested in the Simon task to assess their inhibition (see the method section of Experiment 1 for more details).

3.2. Results and discussion

Preliminary analyses were run with the block (1st *vs.* 2nd half of the experiment) and item difficulty (i.e., easy, medium, and difficult items) factors. Main effects of block and of item difficulty were found. Participants were faster during the second than during the first block (i.e., 850 ms and 900 ms, respectively; $F(1, 58) = 20.68$, $MSe = 43779$, $n^2p = .26$, $p < .001$) and on easy than on medium or difficult items (i.e., 852 ms, 881 ms, and 891 ms, respectively; $F(1, 58) = 18.71$, $MSe = 18287$, $n^2p = .24$, $p < .001$). The Age × Block interaction was significant showing larger differences between blocks 1 and 2 in young adults were 74-ms than in older adults (28-ms; $F(1, 58) = 4.70$, $MSe = 43779$, $n^2p = .08$, $p < .05$). Moreover, participants made more errors on difficult than on medium, or easy items (i.e., 34 %, 23 %, and 16 % respectively; $F(1,58) = 142$, $MSe = 70$, $n^2p = 0.42$, $p < 0.001$; see Appendix A). No other main or interaction effects involving these two factors came out significant.

3.2.1. Age-related changes in SMCE during adulthood in the dot comparison task

3.2.1. a Response times. Mean response times and error rates were analyzed using 2 (Age: Young, Older adults) × 2 (Congruency on the previous items: Congruent, Incongruent) 2 (Congruency on the current items: Congruent, Incongruent) mixed-design ANOVAs, with age as the only between-participants factor (see means in Table 4; see Appendix D for summary of statistical results).

Table 4
Young and older adults' mean response times (in ms) and percentages of errors in the dot comparison task for current congruent and incongruent items following congruent or incongruent items (standard deviation in parentheses).

	Young adults (23-year-olds)			Older adults (76-year-olds)		
	Congruency of previous items			Congruency of previous items		
Congruency of current items	C	I	*Means*	C	I	*Means*
	Mean response times (in ms)					
C	719 (147)	746 (145)	733 (144)	925 (154)	952 (159)	939 (153)
I	810 (157)	799 (155)	805 (153)	1030 (128)	1017 (127)	1024 (122)
CE	91***	53***	72***	105***	65***	85***
	Mean percentage of errors					
C	10 (9)	13 (9)	12 (9)	14 (11)	15 (14)	14 (12)
I	35 (17)	37 (16)	36 (15)	36 (18)	35 (15)	36 (17)
CE	25	24	24***	22	20	22***

Note. C = Congruent, I = Incongruent, *CE* = Congruency effects (Incongruent items – Congruent items).
* $p < .05$.
** $p < .01$.
*** $p < .001$.

Participants (i.e., young and older adults) were 78-ms faster on current congruent items than on current incongruent items ($F(1, 58) = 91.50$, $MSe = 4031$, $\eta^2p = .61$, $p < .001$). Most importantly, the significant Congruency on the previous items × Congruency on the current items interaction ($F(1, 58) = 11.02$, $MSe = 2018$, $\eta^2p = .16$, $p < .01$; Fig. 5) revealed larger congruency effects on current items following congruent items (98 ms; $F(1, 58) = 144.23$, $\eta^2p = .71$, $p < .001$) than after incongruent items (60 ms; $F(1, 58) = 25.83$, $\eta^2p = .31$, $p < .001$). SMCE were found in young (38 ms) and older (39 ms) adults; the Age × Congruency on the previous items × Congruency on the current items interaction was not significant ($F < 1$).

3.2.1. b Error rates. Analyses of errors revealed only a significant main effect of congruency ($F(1, 58) = 54.07$, $MSe = 576$, $\eta^2p = .48$, $p < .001$). Participants made more errors on incongruent (36 %) than on congruent items (13 %).

3.2.2. Age-related changes in SMCE during adulthood in the Simon task

3.2.2. a Response times. Mean response times and percentages of errors on each item (see Table 5) were analyzed using 2 (Age: Young, Older adults) × 2 (Congruency on the previous items: Congruent, Incongruent) × 2 (Congruency on the current items: Congruent, Incongruent) mixed-design ANOVAs, with age as the only between-participants factor (see Appendix E for summary of statistical results).

Young adults were 113-ms faster than older adults ($F(1, 58) = 24.15$, $MSe = 7843$, $\eta^2p = .29$ $p < .001$), and all participants were 35-ms faster on current congruent than on current incongruent items ($F(1, 58) = 57.39$, $MSe = 1302$, $\eta^2p = .50$, $p < .001$). Most importantly, the Age × Congruency on the current items interaction was significant ($F(1, 58) = 11.13$, $MSe = 1302$, $\eta^2p = .16$, $p < .001$). Congruency effects on current items were larger in older (51 ms; $F(1, 27) = 35.05$, $MSe = 2073$, $\eta^2p = .57$, $p < .001$) than in young adults (20 ms; $F(1, 31) = 19.88$, $MSe = 630$, $\eta^2p = .39$, $p < .01$).

Finally, the significant Congruency on the previous items × Congruency on the current items interaction ($F(1, 58) = 110.96$, $MSe = 891$, $\eta^2p = .66$, $p < .001$, Fig. 6) revealed larger congruency effects on current items following congruent items (76 ms; $F(1, 58) = 155.19$, $\eta^2p = .73$, $p < .001$) and smaller congruency effects following incongruent items (-6 ms; $F < 1$). SMCE were found in young

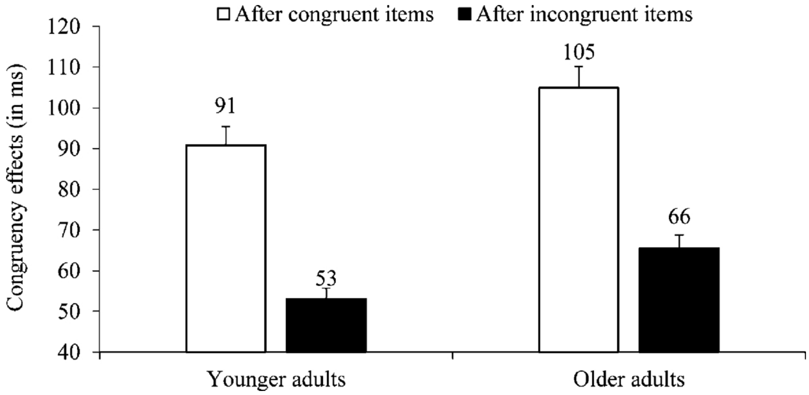


Fig. 5. SMCE (i.e., congruency effects on current items after congruent items – congruency effects on current items after incongruent items) in the dot comparison task for young and older adults. Error bars represent Confidence Intervals at 95 %.

Table 5
Young and older adults' mean response times (in ms) and percentages of errors in the Simon tasks for current congruent or incongruent items following congruent or incongruent items (Standard Deviation in parentheses).

	Young adults (23-year-olds)			Older adults (76-year-olds)		
	Congruency of previous items			Congruency of previous items		
Congruency of current items	C	I	*Means*	C	I	*Means*
	Mean response times (in ms)					
C	416 (64)	454 (71)	435 (67)	507 (98)	556 (113)	532 (103)
I	472 (66)	437 (66)	455 (65)	603 (124)	562 (123)	583 (121)
CE	56***	−17*	20***	96***	6	51***
	Mean percentage of errors					
C	3 (4)	6 (6)	4 (4)	67 (7)	8 (8)	7 (7)
I	13 (11)	4 (6)	9 (8)	14 (14)	10 (10)	12 (8)
CE	10***	−2	5*	8***	2	5***

Note. C = Congruent, I = Incongruent, *CE* = Congruency effects (Incongruent items – Congruent items).
*$p < .05$.
**$p < .01$.
***$p < .001$.

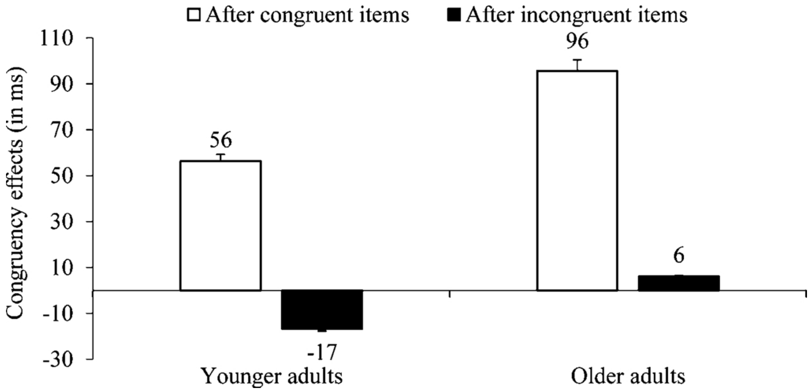


Fig. 6. SMCE (i.e., congruency effects on current items after congruent items – congruency effects on current items after incongruent items) in the Simon task for young and older adults. Error bars represent Confidence Intervals at 95 %.

(73 ms) and older (90 ms) adults; the Age × Congruency on the previous items × Congruency on the current items interaction was not significant ($F < 1$).

3.2.2. b Error rates. Participants made fewer errors on current congruent (6 %) than on current incongruent items (11 %, $F(1, 58) = 18.50$, $MSe = 63$, $n^2p = .24$, $p < .001$). Also, the significant Congruency on the previous items × Congruency on the current items interaction ($F(1, 58) = 65.66$, $MSe = 20$, $n^2p = .53$, $p < .001$) revealed larger congruency effects on current items following congruent items (9 %; $F(1, 58) = 50.64$, $n^2p = .47$, $p < .001$) than after incongruent items (- 0.3 %; $F < 1$). Most importantly, the Age × Congruency on the previous items × Congruency on the current items interaction was significant ($F(1, 58) = 7.53$, $MSe = 20$, $n^2p = .12$, $p < .01$). SMCE were larger in young ($F(1, 31) = 46.86$, $MSe = 27$, $n^2p = .60$, $p < .001$) than in older adults ($F(1, 27) = 29.54$, $MSe = 11$, $n^2p = .50$, $p < .001$).

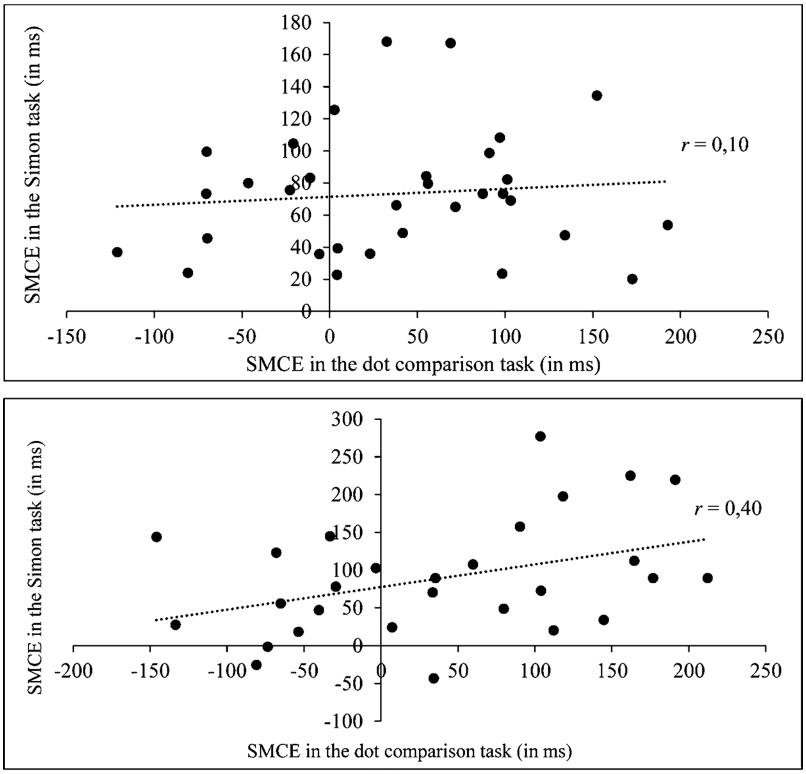
3.2.3. Relations among sequential modulations effects in dot comparison and Simon tasks

As in children, correlation analyses between SMCE in both dot comparison and Simon tasks were conducted to test individual differences during aging (Lemaire & Hinault, 2014). Significant correlation between SMCE in both dot comparison and Simon tasks (i.e., response times) was found in older adults ($r = .40$; $df = 26$; $p < .05$, Fig. 7a) but not in young adults ($r = .10$, $df = 30$, Fig. 7b). This result suggests that older adults with larger SMCE in the Simon task obtained larger SMCE in the dot comparison task.

To further examine individual differences in older adults' SMCE in the dot comparison task, this group was divided into two groups (i.e., based on SMCE in responses times in the Simon task), so-called low- and high-SMCE-Simon groups. The low- and high-SMCE-Simon groups included respectively the 14 older adults with the smallest (30 ms) and the largest (149 ms) SMCE in the Simon task.[6]

[6] SMCE in the Simon task ranged from -43ms to 277 ms. The median (i.e., 83 ms) was used to divide participants into two groups. Thus, participants with SMCE smaller than 83 ms were in the "Low-SMCE-Simon" group (*mean* = 30 ms), whereas the other 14 participants with SMCE larger than 83 ms were in the "High-SMCE-Simon" group (i.e., *mean* = 149 ms).

(a) Younger adults



(b) Older adults

Fig. 7. Correlations between SMCE (i.e., congruency effects on current items following congruent items – following incongruent items) in dot comparison and Simon tasks in (a) young and (b) older adults.

Note that these two groups did not differ (*Fs* < 1) in their mean age, verbal fluency, years of formal education, score in MMSE (see Table 6), or mean congruency effects on current items in the dot comparison task (108 ms *vs*. 63 ms in high- and low-SMCE-Simon groups, respectively).

3.2.4. Comparing high- and low-SMCE-Simon older adults in the dot comparison task

Mean response times and error rates on the current items were analyzed using 2 (Group: Low-, High-SMCE-Simon) × 2 (Congruency on the previous items: Congruent, Incongruent) × 2 (Congruency on the current items: Congruent, Incongruent) mixed-design ANOVAs, with group as between-participants factors (Fig. 8).

3.2.4. a Response times. All older adults were 85-ms faster on current congruent items than on current incongruent items ($F(1, 26) = 34.47$, $MSe = 5899$, $n^2p = .57$, $p < .001$). They sequentially modulated congruency effects, as shown by a significant interaction between congruency on the previous items and congruency on the current items ($F(1, 26) = 4.66$, $MSe = 2331$, $n^2p = .15$, $p < .05$). Furthermore, the Group × Congruency on the previous items × Congruency on the current items was significant ($F(1, 26) = 3.47$, $MSe = 4.02$, $n^2p = .13$, $p < .05$), showing that high-SMCE-Simon group sequentially modulated congruency effects (76 ms, $F(1, 13) = 7$, $MSe = 2886$, $n^2p = .35$, $p < .05$), whereas low-SMCE-Simon group did not (3 ms, $F < 1$).

3.2.4. b Error rates. Analyses of errors only revealed a main effect of congruency on the current items ($F(1, 26) = 18.40$, $MSe = 690$, $n^2p = .41$, $p < .001$), showing that both groups made more errors on current incongruent items (36 %) than on current congruent items (14 %).

3.2.5. Comparing High-SMCE-Simon older adults and young adults in the dot comparison task

Mean response times and error rates on the current items were analyzed using 2 (Age: Young, high-SMCE-Simon older adults) × 2 (Congruency on the previous items: Congruent, Incongruent) × 2 (Congruency on the current items: Congruent, Incongruent) mixed-design ANOVAs, with age as the only between-participants factor (Fig. 8) to compare young adults and high-SMCE-Simon older adults.

3.2.5. a Response times. Young adults were 260-ms faster than high-SMCE-Simon older adults ($F(1, 44) = 36.92$, $MSe = 17830$, $n^2p = .46$, $p < .001$). All participants were 67-ms faster on current congruent items than on current incongruent items ($F(1, 26) = 34.47$, $MSe = 5899$, $n^2p = .57$, $p < .001$). The significant Congruency on the previous items × Congruency on the current items

Table 6
Older adults' characteristics.

	Low-SMCE-Simon group		High-SMCE-Simon group	
	M	SD	M	SD
n	14	–	14	–
Males/females	3/11	–	5/9	–
Mean age	75	9.8	78	8.9
Years of formal education	14	4.0	13	4.3
MHVS	25	5.0	23	7.3
MMSE	29	1.0	28	1.8

Note. MHVS = French version of the Mill-Hill Vocabulary Scale (Deltour, 1993; Raven, 1951). MMSE = Mini Mental State Examination (Folstein et al., 1975).

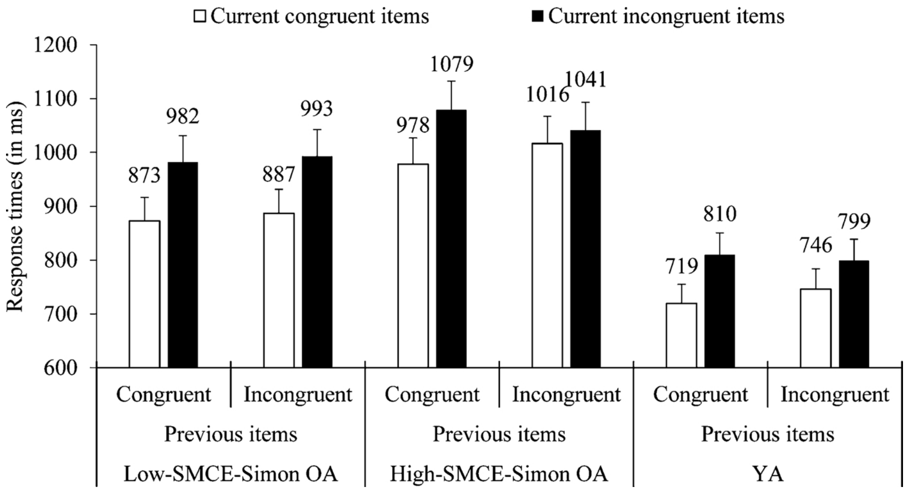


Fig. 8. Low- and High-SMCE-Simon older adults (OA) and young adults' (YA) mean response times on current congruent or incongruent items following congruent or incongruent items. Error bars represent Confidence Intervals at 95 %.

interaction ($F(1, 44) = 16.39$, $MSe = 1922$, $n^2p = .27$, $p < .001$) revealed larger congruency effects on current items following congruent items (96 ms; $F(1, 44) = 110.93$, $p < .001$) than after incongruent items (39 ms; $F(1, 44) = 9.90$, $p < .001$). Most importantly, SMCE were found in young (35 ms) and older (76 ms) adults; the Age × Congruency on the previous items × Congruency on the current items interaction was not significant ($F < 1$).

3.2.5. b Error rates. Error analyses only revealed a main effect of congruency ($F(1, 44) = 27.38$, $MSe = 532$, $n^2p = .38$, $p < .001$), showing that participants made more errors on current incongruent items (34 %) than on current congruent items (15 %).

In summary, age-related differences in SMCE during adulthood depended on the efficiency of executive control processes. We found that older adults with highly efficient executive control processes, as assessed in the Simon task, presented SMCE, whereas older adults with less efficient executive control processes did not.

4. General discussion

This study contributes to our understanding of how participants accomplish numerosity comparison tasks. It is the first study to find evidence of sequential modulations of congruency effects (SMCE) in numerosity comparison tasks and age-related differences in these modulations throughout the lifespan. Oldest children (13-year-olds), young (23-year-olds) and older adults (76-year-olds) sequentially modulated congruency effects, as shown by congruency effects on current items following incongruent items but not after congruent items. Moreover, young adults as older adults with efficient executive control processes (i.e., high-SMCE-Simon older adults), sequentially modulated congruency effects, whereas older adults with less efficient executive control processes (i.e., low-SMCE-Simon older adults) did not. These findings have important implications to further our understanding of mechanisms involved in numerosity comparison and how these mechanisms change throughout the lifespan.

4.1. Sequential modulations of congruency effect in numerosity comparison

Previous works revealed that numerosity comparison involves both domain-general and domain-specific processes. The present findings contribute to our understanding of the role of domain-general executive control processes in numerosity comparison performance. Consistent with previous findings on congruency effects in numerosity comparison tasks (e.g., Barth et al., 2006; Cappelletti et al., 2014; Clayton & Gilmore, 2015; Clayton et al., 2015; Fush & McNeil, 2013; Gebuis & Reynvoet, 2012; Gilmore et al., 2013; 2016; Gilmore et al., 2015; Halberda et al., 2008; Inglis & Gilmore, 2014; Libertus et al., 2011; Nys & Content, 2012), we found poorer performance on incongruent than on congruent items. This is usually accounted for by assuming that processing incongruent items requires additional processes to inhibit irrelevant information (i.e., convex hull) in order to focus on relevant information (i.e., numerosity) on incongruent items.

Most originally, we found SMCE (i.e., congruency effects on current items were smaller following incongruent than after congruent items) in the dot comparison task. One interpretation of the present SMCE in numerosity comparison tasks is that SMCE involve the same type of executive control processes that have been assumed by theories of executive control (e.g., Botvinick et al., 2001; Braver, 2012; Bugg & Crump, 2012; De Pisapia & Braver, 2006; Mayr & Awh, 2009; Scherbaum, Dshemuchadse, Ruge, & Goschke, 2012). For instance, Braver's theory (2012) describes sequential congruency effects as involving the coordination of two modes of control: the reactive and proactive control (see also Bugg & Crump, 2012). The reactive control refers to conflict detection and resolution when no preparation to process conflict has been engaged. Conversely, the proactive control referes to the coordination of activations toward a goal and the preparation for conflict processing. In line with this theory, we can hypothesize that executive control processes detect and resolve an interference between numerosity and convex hull on incongruent items. This in turn leads the executive system to increase its level of control in order to more efficiently resolve the interference on the next items. That is, after processing interference between numerosity and convex hull on previous incongruent items, participants increase the level of executive control on current incongruent items (suggesting proactive control) to inhibit the irrelevant and misleading visual features (i.e., convex hull), and to respond only on the basis of numerosity. In contrast, following congruent items, executive control is less involved. Participants did not prepare themselves (suggesting reactive control) for processing subsequent incongruent items and are less efficient at processing conflict information.

A question that arises is whether mechanisms involved in processing congruency and in SMCE are specific to this dot comparison task, or whether they reflect what happens in other numerosity comparison tasks. To answer this, future research could test whether effects of visual features (e.g., size or arrangement of items, stimulus display, filled area) of current dot collections are modulated by visual features of immediately preceding dot collections in a variety of numerosity comparison tasks (e.g., providing number of dot collections, finding approximate number of dots of several collections displayed either simultaneously or sequentially).

At a very general level, sequential effects found here suggest that numerosity comparison bear similarities to a number of other cognitive tasks with regards to reliance on mechanisms enabling participants to modulate executive control, and possibly other mechanisms across successive items. Indeed, in a wide variety of cognitive tasks, ranging from domain-general executive control tasks like Stroop or Simon tasks (e.g., Gratton et al., 1992) or domain-general episodic memory tasks (e.g., Hinault, Lemaire et al., 2016) to domain-specific tasks like arithmetic problem solving (e.g., Uittenhove & Lemaire, 2012) or lexical decision tasks (Taylor & Lupker, 2001), previous research found that performance on current items are not only influenced by features of the current items but also by features of the preceding items. This suggests that in numerosity comparison, like in other cognitive tasks, participants do not process the current items independently of the preceding items. Although this has been found in different cognitive tasks and domains, it was not obvious that this may also happen in numerosity comparison. Indeed, numerosity comparison relies heavily on the approximate number system (ANS), a cognitive system that gives rise to our numerical intuition via basic numerical processes and present from birth to old age in humans as well as in different animal species (e.g., Feigenson et al., 2004). As a consequence, participants may accomplish numerosity comparison tasks without using information from preceding items to improve performance on current items. Our results showed that it is not the case. Indeed, like in other cognitive tasks, in comparison tasks participants do not process current items independently of preceding items.

4.2. Sequential modulations of congruency effect in numerosity comparison throughout the lifespan

The most important result of this research concerns how the capacity to sequentially modulate the congruency effects emerges and becomes effective throughout the lifespan. Indeed, SMCE was only found in 13-year-olds, not in 10-year-olds, and reverse in 8-year-olds.

We assume that 13-year-olds did exactly like adults. That is, children prepared themselves to process incongruent items after processing incongruent items (see Fig. 9). This preparation led them to increase their level of executive control on current incongruent items to more quickly inhibit the irrelevant and misleading visual information and to focus their attentional resources on the relevant numerosity information. Moreover, as in adults, they did not prepare themselves to process incongruent items after congruent items, leading them to take extra time to inhibit irrelevant visual information and to focus on relevant numerosity information.

Congruency effects on current items were present after both congruent and incongruent items in 10-year-old-children. This result indicates that at age 10, children were not yet able to sequentially modulate executive control processes efficiently. Indeed, it would have enabled them to process incongruent items following incongruent items more efficiently than after congruent items, like 13-year-old-children and adults did. Most likely, limitations in their executive control resources prevented them from preparing themselves to process incongruent items efficiently after processing incongruent items. In fact, they increased their latencies on current incongruent items more following incongruent items than after congruent items. This is similar to what has been often found in the literature, namely sequential difficulty effects (SDE). In SDE, participants' performance is poorer on current items following harder items than after easier items (e.g., Hofmann, Schmeichel, & Baddeley, 2012; Schmeichel, 2007; Schneider & Anderson, 2010; Uittenhove & Lemaire, 2012). This occurs because participants use more resources on harder items and have fewer resources left free

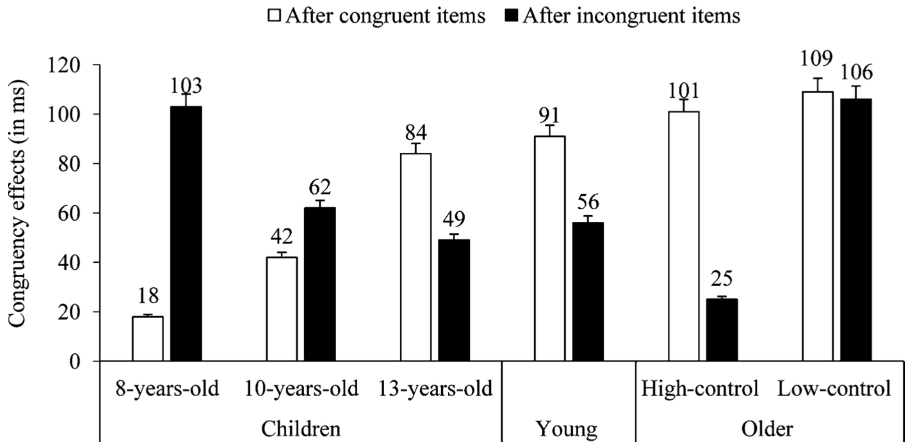


Fig. 9. SMCE (i.e., congruency effects on current items after congruent items – congruency effects on current items after incongruent items) in the dot comparison task throughout the lifespan. Error bars represent Confidence Intervals at 95 %.

for the immediately following items. Here, we can hypothesize that 10-year-old-children used additional (executive) resources to process current incongruent items leading them to have fewer resources available for processing the following items. In other words, limited executive control resources in 10-year-old-children led them to only reactively process current incongruent items and to process each item independently of the immediately preceding item.

Eight-year-old-children showed reversed SMCE (i.e., congruency effects were present on current items following incongruent items but not after congruent items). It was surprising to observe no congruency effects in 8-year-old-children on current items following congruent items. It is difficult to know if these 8-year-olds focused on numerosity of the previous items and were not influenced by convex hull information. To test this possibility, we conducted additional analyses,[7] and we proposed that younger children may have been primed at focusing on numerosity of current items following congruent items.

An alternative explanation concerns strategies used to accomplish dot comparison tasks. Indeed, previous studies reported that participants use several strategies to estimate numerosities and compare numerosities of collections of dots, and that strategies vary with participants' age (Gandini, Lemaire, & Dufau, 2008; Gandini, Lemaire, & Michel, 2009; Roquet & Lemaire, 2019; Siegel, Goldsmith, & Madson, 1982). For example, Roquet and Lemaire (2019) collected verbal protocols when young and older adults had to select the largest array in the dot comparison task. Analyses of these verbal protocols led them to find that, based on visual features of dot collections, both young and older adults used a set of 9 strategies and selected strategies on a trial-by-trial basis. Furthermore, they observed that participants used significantly more strategies on congruent items than on incongruent items. This suggests that differences in strategies may explain differences in congruency effects on current items following congruent versus incongruent items. Lack of congruency effects on current items following congruent items in 8-year-old-children should be further investigated using this strategy approach. Thus, developmental changes in children showed that mechanisms responsible for SMCE are fully efficient at age 13. Before, lower levels of maturity in both numerosity and executive control processes do not enable younger (8- and 10-year-olds) children to sequentially modulate inhibition processes while comparing two collections of dots. Such developmental changes in how general executive control processes are involved in a domain-specific task such as numerosity comparison, are somewhat surprising given previous findings on age-related changes in sequential modulations of executive control processes, assessed with conflict tasks like Stroop, Flanker, or Simon tasks. Indeed, many studies using these conflict tasks found SMCE in children aged 5 or more (e.g., Ambrosi et al., 2016; Chatham et al., 2009; Chevalier, 2015; Chevalier et al., 2014; 2015; Lucenet & Blaye, 2014; Smulders, Soetens, & van der Molen, 2018; see Best & Miller, 2010 for a review).

As a consequence, SMCE could be expected in 8- and 10-year-old-children tested here. We did not find this. It is possible that children are able to efficiently use executive control processes that enable them to proactively process incongruency in the context of domain-general tasks such as abstract conflict tasks. However, in the context of domain-specific tasks such as a dot comparison task, it may be harder and take more time for them to do so. This could happen if resources used to execute domain-specific processes necessary to accomplish these tasks do not leave enough resources free to efficiently execute domain-general processes. In other words, after allocating their available resources to specifically process numerosity information (e.g., encoding dots, activating

[7] Additional analyses were conducted to more strongly test the hypothesis that 8-year-olds may have been primed at focusing on numerosity in previous items. We examined the ratio effects on previous items and age-related differences in these ratio effects. The priming hypothesis predicts a ratio effect on the previous item only for 8-year-olds. Mean response times in children were analyzed using a 3 (Age: 8-, 10-, and 13-year-olds) × 2 (Ratio on the previous items: Easy, Hard) × 2 (Ratio on the current items: Easy, Hard) mixed-design ANOVA, with age as the only between-participants. The same analysis was also conducted in adults, using a 2 (Age: Young, Older adults) × 2 (Ratio on the previous items: Easy, Hard) × 2 (Ratio on the current items: Easy, Hard) mixed-design ANOVA, with age as the only between-participants factor. Results showed that ratio effect on the previous items was observed in 8-year-olds but not in the other groups (i.e., 11-year-olds, 13-year-olds, young and older adults), suggesting that younger children may have been primed at focusing on numerosity of current items following congruent items.

memory representation of numerosities, comparing numerosities), 8- and 10-year-old-children may have not enough resources left free to sequentially modulate executive control processes. Moreover, several studies showed that SMCE observed in children might differ depending on the task, suggesting that magnitudes of SMCE can interact with tasks (see Braem, Abrahamse, Duthoo, & Notebaert, 2014, for a review). Current findings can be interpreted similarly. Indeed, we found that developmental changes in SMCE depended on the type of conflict encountered. Age-related differences in SMCE were observed in the dot comparison task but not in the Simon task. In the dot comparison task, the conflict depended on both visual features and the large number of dots while in the Simon task, the conflict is created by the location of the required response and the directional information associated with the arrow. These different types of conflict may require different types of cognitive processes. Consistent with Best and Miller's study (2010), despite their apparent similarities, different conflict tasks can show different ages of mastery, perhaps as a result of different cognitive demands. Thus, it is possible that the efficiency of executive control processes may depend on cognitive demands required by the task (see Rey-Mermet, Gade, & Oberauer, 2018, for a discussion).

The capacity to sequentially modulate congruency effects in the present study was maintained even in older adults (76-year-olds). However, correlation analyses showed important inter-individual' variability among older adults, depending on executive functioning assessed by the Simon task (i.e., older with higher SMCE in Simon task presented also higher SMCE in dot comparison task). These findings suggest that future studies investigating aging effects in numerosity comparison should examine individual differences as some older adults may show preserved performance and others less preserved performance when accomplishing numerosity comparison tasks.

Moreover, it is difficult to make strong inferences from the present differences between ratio effects in adults and children. Recall that only three levels of ratio (smaller, medium, and larger) were used here in order to test items of varying difficulty. With more, continuous levels of ratios, it would be possible to compare ratio effects across age groups, as done in several previous studies (e.g., Halberda & Feigenson, 2008; Halberda et al., 2008; Libertus et al., 2011; Mazzocco, Feigenson, & Halberda, 2011).

To conclude, many previous studies found that numerosity comparison depends on the efficiency of basic numerical processes deployed by a dedicated specific system, the approximate number system (e.g., Dehaene, 1997; Feigenson et al., 2004; Leibovich et al., 2017). The present findings on congruency effects and their sequential modulations throughout the lifespan help to understand how numerosity comparison performance is also influenced by general cognitive mechanisms. We found that processing interference between numerosity and visual properties of the stimulus, as well as sequential modulations of this interference processing that start at the age of 13 (and are inverse at the age of 8) are two key executive control processes that people use when they have to compare numerosities.

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Appendix A. Participants' mean response times (in ms) and percentages of errors in the dot comparison task for easy, medium, and difficult items

	8-year-olds	10-year-olds	13-year-olds	23-year-olds	76-year-olds
Response times					
Easy items	824	823	890	741	965
Medium items	834	849	896	779	983
Difficult items	824	845	896	786	995
Statistical analysis	ANOVA 3 Group × 3 Item difficulty			ANOVA 2 Group × 3 Item difficulty	
	Ratio Effect: F = 1.47; MSe = 13037; n^2p = 0.02			Ratio Effect: F = 18.71, MSe = 18287, n^2p = 0.24	
	Group × Ratio: F = 0.45; MSe = 13037; n^2p = 0.01			Group × Ratio: F = 1.06, MSe = 18287, n^2p = 0.02	
Error rates					
Easy items	35	27	24	15	17
Medium items	40	33	32	23	24
Difficult items	39	32	28	34	34
Statistical analysis	Ratio Effect: F = 14.25; MSe = 66; n^2p = 0.13			Ratio Effect: F = 142, MSe = 70, n^2p = 0.42	
	Group × Ratio: F = 0.39; MSe = 66; n^2p = 0.01			Group × Ratio: F = 0.48, MSe = 70, n^2p = 0.01	

Appendix B. Statistics of Effects in Experiment 1 for response times (in ms) and percentages of errors in the dot comparison task

Effects	*MSe*	*F*	$\eta^2 p$
Response Times			
Group	31030	1.29	0.27
Congruency on the previous items	4950	0.01	0
Congruency on the current items	2210	155.60***	0.63
Group × Congruency on the previous items	4950	1.30	0.03
Group × Congruency on the current items	2210	0.80	0.02
Congruency on the previous items × Congruency on the current items	3063	4.20*	0.04
Group × Congruency on the previous items × Congruency on the current items	3063	9.45***	0.17
Error Rates			
Group	57	12.07***	0.21
Congruency on the previous items	322	0.12	0
Congruency on the current items	985	8.27**	0.08
Group × Congruency on the previous items	322	0.54	0.01
Group × Congruency on the current items	985	4.11*	0.08
Congruency on the previous items × Congruency on the current items	31	18.62***	0.17
Group × Congruency on the previous items × Congruency on the current items	31	0.11	0

Appendix C. Statistics of Effects in Experiment 1 for response times (in ms) and percentages of errors in the Simon task

Effects	*MSe*	*F*	$\eta^2 p$
Response Times			
Group	7824	47.22***	0.50
Congruency on the previous items	1126	0.99	0.01
Congruency on the current items	2265	64.89***	0.41
Group × Congruency on the previous items	1126	1.43	0.03
Group ×x Congruency on the current items	2265	6.61**	0.12
Congruency on the previous items × Congruency on the current items	1898	78.46***	0.46
Group × Congruency on the previous items × Congruency on the current items	1898	1.10	0.02
Error Rates			
Group	50	3.49*	0.07
Congruency on the previous items	26	9.76**	0.10
Congruency on the current items	86	44.14***	0.32
Group × Congruency on the previous items	26	0.90	0.02
Group × Congruency on the current items	86	3.18*	0.06
Congruency on the previous items × Congruency on the current items	41	120.71***	0.57
Group × Congruency on the previous items × Congruency on the current items	41	0.75	0.16

Appendix D. Statistics of Effects in Experiment 2 for response times (in ms) and percentages of errors in the dot comparison task

Effects	*MSe*	*F*	$\eta^2 p$
Response Times			
Group	19732	34.17	0.37
Congruency on the previous items	1786	1.80	0.03
Congruency on the current items	4031	91.50***	0.61
Group × Congruency on the previous items	1786	0.02	0
Group × Congruency on the current items	4031	0.65	0.01
Congruency on the previous items ×x Congruency on the current items	2018	11.02**	0.16
Group × Congruency on the previous items × Congruency on the current items	2018	0.01	0
Error Rates			
Group	47	0.25	0
Congruency on the previous items	30	2.68	0.04
Congruency on the current items	576	54.07***	0.48
Group × Congruency on the previous items	30	0.24	0
Group × Congruency on the current items	576	0.24	0
Congruency on the previous items × Congruency on the current items	39	0.68	0.01
Group × Congruency on the previous items × Congruency on the current items	39	0	0

Appendix E. Statistics of Effects in Experiment 2 for response times (in ms) and percentages of errors in the Simon task

Effects	*MSe*	*F*	$\eta^2 p$
Response Times			
Group	7843	24.15***	0.29
Congruency on the previous items	576	0.85	0.01
Congruency on the current items	1302	57.39***	0.50
Group × Congruency on the previous items	576	0.75	0
Group × Congruency on the current items	1302	11.13***	0.16
Congruency on the previous items × Congruency on the current items	891	110.96***	0.66
Group × Congruency on the previous items × Congruency on the current items	891	0.30	0.02
Error Rates			
Group	87	1.83	0.03
Congruency on the previous items	21	13.07***	0.18
Congruency on the current items	63	18.50***	0.24
Group × Congruency on the previous items	21	0.84	0.01
Group × Congruency on the current items	63	0.10	0
Congruency on the previous items × Congruency on the current items	20	65.66***	0.53
Group × Congruency on the previous items × Congruency on the current items	20	7.53**	0.12

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