

Developmental trajectories of metacognitive processing and executive function from childhood to older age

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Developmental trajectories of metacognitive processing and executive function from childhood to older age

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Keywords: Metacognitive processing, metacognition, executive functions, developmental trajectories, cognitive development, bilingualism, bilingual advantage.

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Abstract

Modern understanding of the term metacognition encompasses two levels of processing: a lower level *awareness* or *knowledge* of one's own thoughts and a higher level *regulation* or *control* of our thinking (Fleming et al., 2014). Metacognition, therefore, bears conceptual similarity with executive function: both are concerned with top down monitoring and control of cognition in the service of ongoing goal-directed behaviour. Previous studies have shown a possible executive function advantage in multilingual speakers but also a possible disadvantage in metacognitive processing (Folke et al., 2016). In order to progress theory on metacognitive processing and the relationship with executive function and linguistic experience across the lifespan, we conducted a study testing 330 healthy individuals in 4 age groups from 7 to 80 years old. Participants all performed a metacognition task and two measures of executive function, which included the Simon task and the Tower of London task. Half the participants were multilingual speakers since birth.

We built developmental trajectories of metacognitive and executive function across the lifespan. Best metacognitive efficiency was observed in mid-adulthood, whereas best executive function processing reached its peak in young adulthood. A steep cognitive decline was observed in older age, whilst metacognitive efficiency was preserved. Exploratory factor analysis indicated that metacognition and executive function are served by different factors across all ages. Contrary to previous findings in the bilingual literature, a multilinguistic experience neither conferred any significant advantage nor disadvantage in both executive function and metacognitive processing across the lifespan.

Keywords: *Metacognition, Metacognitive Processing, Executive Function, Multilingualism, Bilingualism, Developmental Trajectories*

Introduction

What is metacognition

Modern understanding of metacognition as encompassing both a relatively passive (knowledge/awareness) function and an active (regulatory/control) function suggests conceptual overlap with mechanisms associated with executive function and cognitive control. In this study we focus on the relationship between executive function and metacognitive abilities from childhood to older age.

The concept of metacognition originated in the early 1970s with an early focus on knowledge and monitoring of memory storage and retrieval, referred to as *metamemory* (Flavell, 1971). Within Flavell's framework, metamemory skills provide optimized memory performance through the active regulation of subjective estimates of performance against actual performance (Roehrs, 2017). Active *control* as well as more passive monitoring were also subsequently incorporated within a broader concept of metacognition by Flavell (1979) in order to describe the monitoring and control of all declarative cognitive activity. Under this framework, metacognition operates on two interacting levels: an object level (bottom up cognitive monitoring) and a meta-level (top down control; Nelson & Narens 1990, 1994). This meta-level bears similarity with Norman & Shallice's (1986) model of executive function in which available action sequences (or schema) currently competing for selection are monitored and manipulated by a supervisory attentional system in the service of purposive, goal-directed behaviour (Fernandez-Duque et al., 2000). Arguably, therefore, the meta-level and executive systems operate comparably in the way that they modulate information via top-down control.

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3 Intuitively, if metacognition is closely associated with mechanisms of cognitive
4 control, we should predict that scores on tests of metacognitive ability and executive
5 function would be highly correlated. Consistent with this view, evidence indicates that
6 switching of attention from one task demand to another supports the ability to provide
7 consistent/accurate performance judgements (Del Missier et al., 2010) as well as
8 prospective confidence judgements (feeling-of-knowing) on a metamemory task
9 involving memorizing cue-target word combinations (Boduroglu et al., 2014).

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19 Successful organisation of our activities relies not just on our ability to resist strong
20 goal-irrelevant response tendencies or to sustain attention through to the completion
21 of a task, but also to determine the relationship between our actions and our objective
22 performance towards a goal. Without accurate monitoring (i.e., where perceived level
23 of performance is poorly calibrated with actual performance), we are unable to
24 optimally regulate our knowledge or strategies in the service of goal attainment. Thus,
25 metacognitive processing can be considered a fundamental requirement for successful
26 behaviour, because optimal efficiency in performance is contingent upon the
27 calibration of actual against self-estimated progress or attainment. Consistent with this
28 claim, for example, a large body of evidence indicates that actual achievement in
29 educational settings is highly sensitive to calibration accuracy (for a review, see Bol
30 & Hacker, 2012).

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47 While it is firmly established that fluid intelligence and cognitive control are sensitive
48 to age, with steep declines typically observed in ageing populations, the lifespan
49 trajectory of metacognitive abilities is less certain. Some authors highlight the role of
50 fronto-parietal networks underpinning metacognitive performance (e.g., Fleming,
51 Huijgen & Dolan, 2012; McCurdy et al., 2013), again perhaps indicating that
52 cognitive mechanisms associated with metacognition are shared with those serving
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3 general intelligence and executive control (e.g., Barbey, Colom, Solomon, Forbes &
4 Grafman, 2012; Yoon et al., 2017). To the extent that this is true, one might predict
5 that metacognitive skills would follow the same age-related trajectory observed for
6 measures of executive function. Evidence for a disproportionate mismatch between
7 confidence in abilities and actual performance on relevant tasks in older individuals
8 compared to younger individuals is largely consistent with this prediction (e.g.,
9 Dodson, Bawa, & Krueger, 2007; Hansson, Rönnlund, Juslin, & Nilsson, 2008) yet
10 other studies have indicated similar metacognitive performance in older and younger
11 participants (e.g., Eakin, Hertzog & Harris, 2014; Halamish, McGillivray & Castel,
12 2011), and a recent study of perceptual and memory metacognitive ability found no
13 evidence for a meaningful relationship between metacognition and executive function
14 in either domain (Palmer, David, & Fleming, 2014).

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16 Some research (e.g., Stankov, 1998; Stankov & Crawford, 1997) indicates that actual
17 performance and confidence ratings differ with respect to the type of task being
18 employed (e.g., people tend to be overconfident on tests of general knowledge and
19 under-confident on perceptual tasks typically employed in experimental psychology).
20 This observation has led authors (e.g., Juslin & Olsson, 1997) to claim that different
21 tasks are associated with different (and independent) metacognitive processes.
22 However, very high correlations observed in confidence ratings across diverse tasks,
23 including those tapping general knowledge and perceptual discrimination (e.g.,
24 Stankov, 1998, 2000), have encouraged an alternative claim to emerge: that one
25 metacognitive system underpins self-monitoring ability irrespective of the task
26 undertaken (e.g., Baranski & Petrusic, 1994; Ferrell, 1995; Pallier et al., 2002;
27 Stankov, 2000), with variations in confidence across tasks explained by general task
28 difficulty rather than differences in the underpinning psychological processes.
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3 Moreover, the developmental literature indicates a trajectory from task specificity in
4 metacognitive abilities in young children, with a unitary, domain general
5 metacognitive system (i.e., one that is drawn upon irrespective of task) emerging by
6 the age of around 15 years (e.g., Schraw, Dunkle, Bendixen, & Roedel, 1995;
7 Veenman, Wilhelm, & Beishuizen, 2004; Veenman & Spaans, 2005).

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10 A current issue of considerable current debate is whether the limited capacity and
11 goal-directed selectivity of our executive system can somehow be enhanced or
12 otherwise benefit from the continuous, intense competition associated with
13 multilingual environments (e.g., Bialystok, Craik & Luk, 2012; see also Paap,
14 Johnson & Sawi, 2014, for an alternative view). Despite the large body of literature
15 focused on this question, and the conceptual overlap between cognitive control and
16 metacognition, very few studies have explicitly addressed the possibility that
17 multilingualism may impact on metacognitive processing. There is evidence that
18 bilingual university students have better insight into their reading comprehension
19 abilities compared to their monolingual peers (Ransdell et al., 2006), that children
20 who learned a second language in a formal context display an increased awareness
21 and use of communicational strategies (Le Pichon Vorstman et al., 2009; Le Pichon
22 et al. 2010), and that proficient multilingualism is associated with the flexible use of
23 grammatical (Kemp, 2009) as well as reading strategies (García et al., 1998).
24
25 However, only one study has been published to date which focuses on non-linguistic
26 metacognitive abilities in multilingual individuals. Folke, Ouzia and colleagues
27 (2016) administered a computer-based two-alternative-forced-choice task. In a first
28 order condition, participants judged which of two simultaneously presented circles
29 contained the most number of dots. In the second order condition, participants stated
30 their confidence level in each choice. In two variants of this task, bilinguals were
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3 found to respond faster than monolinguals but were significantly less metacognitively
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5 *efficient*, with efficiency mathematically determined by the difference between
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7 expected and observed performance. Thus, bilinguals were less confident in trials they
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9 completed correctly and more confident in trials where their performance was
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11 incorrect.
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14 In the context of the purported bilingual cognitive advantage (Bialystok, 2018),
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16 evidence that there may be metacognitive *disadvantages* associated with
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18 multilingualism indicates some degree of dissociability of metacognition and
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20 executive function – and we might also observe disparity in the underlying neural
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22 signatures. In a recent review, Roebers (2017) brought together a timely review of the
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24 literature on metacognition and executive function in order to build a unifying
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26 framework for developing theoretical understanding of cognitive self-regulation.
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28 Nevertheless, to date, the literature on bilingual cognition focuses almost exclusively
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30 on executive function and neglects metacognition, possibly because the two research
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32 fields are rooted in quite different research traditions. Consolidating executive
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34 function and metacognition research and applying this to specific contexts such as
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36 multilingual cognition, therefore, constitutes an important avenue for further work.
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3 *Rationale for this study*
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7 Studies of metacognitive processing and executive function are usually based on
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9 constrained age groups in typical, atypical and clinical circumstances. In this study we
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11 employ a cross-sectional design to explore how these crucial cognitive skills evolve
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13 and decline across the lifespan, from the age of 7 to 80 years of age (see Filippi et al.
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15 2019, for a more exhaustive account of developmental approach to bilingual
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17 research). This approach has been successfully used in studies comparing the
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19 development of typical and atypical children (Annaz, Karmiloff-Smith, Johnson &
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21 Thomas, 2009; Karmiloff-Smith, Thomas, Annaz, Humphreys, Ewing, Brace et al.,
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23 Thomas, 2009; Karmiloff-Smith, Thomas, Annaz, Humphreys, Ewing, Brace et al.,
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25 2004; Thomas, Annaz, Ansari, Serif, Jarrold & Karmiloff-Smith, 2009) and in a study
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27 of healthy adults (Palmer, David, & Fleming, 2014).
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30 The primary objectives in the present study were to i. broaden the focus to consider
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32 metacognition and executive function across the lifespan from childhood, through
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34 young, middle and older adulthood, ii. explore how the relationship between these
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36 abilities changes as a function of age and iii., determine whether and how linguistic
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38 experience modulates the trajectory of these effects.
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Methods

Participants

Three-hundred and thirty (330) typically developing individuals took part in this study. Their age ranged from 7 to 80 years old. Half of them were English monolinguals and the other half were bilinguals/multilinguals of different linguistic backgrounds. They were split in four age groups (Petry, 2002): 1) childhood 7-12 years, 2) young adulthood, 18-35 years, 3) middle adulthood, 36-55 years, and 4) older adulthood, 56-80 years old. Mean ages and standard deviations are reported in Table 1 below.

All participants completed an online questionnaire¹ (Filippi et al., 2020) designed to establish demographic, socio-economic and linguistic information. Within the multilingual sample, all individuals reported acquiring two languages from birth (simultaneous bilinguals), and using them on a daily basis at home and with the extended family. Fifty-nine individuals reported to be exposed to a third or a fourth language, although their level of competence in these languages was considered lower. A list of all languages is reported in the online Supplementary Material I, Table A.

All monolingual individuals reported a basic knowledge of some European languages (e.g., French, Spanish or German) learned at school, but were not exposed to or used a foreign language in their daily life, nor had the ability to hold a basic conversation in a language other than English.

All participants also provided socio-economic status information indicating their highest level of education, employment and household income. Each of the adult participants received a score depending on level of academic achievement (i.e., 1=no

¹ Children questionnaire data were provided by their parents.

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3 formal/primary, 2=secondary, 3=undergraduate, 4=post-graduate, 5=doctorate). They
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5 also received a score from 1 to 4 depending on occupation (unemployed, part-time,
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7 full-time, retired), and a score from 1 to 6 depending on total household income (from
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9 less than £20,000 to more than £100,000). Scores were averaged to create a composite
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12 SES score.
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21 *Tasks, Procedure and Materials*

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24 The procedure was approved by the University Ethics Panel (FST/FREP/15/505), and
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26 was conducted in accordance with the tenets of the Declaration of Helsinki.
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29 The experimental battery was conducted on an ASUS laptop with a mouse, standard
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31 keyboard, and a Technopro ® USB gamepad that was adapted with red and blue
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33 colour stickers. All instructions were given in English.
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36 Adult participants were tested in a quiet room made available at Anglia Ruskin
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38 University in Cambridge and at UCL - Institute of Education in London. Child
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40 participants were tested in three primary schools, two in London and one in the
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42 Cambridge area. All children gave their verbal consent before starting the session.
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45 Participants were all assessed on a range of background measures:
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47 ***1. Non-verbal reasoning***

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50 The Raven's Advanced Progressive Matrices Set I (Raven, 1998) was administered.
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52 This test of nonverbal fluid intelligence/problem solving ability consists of 12 items
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54 of increasing complexity. Each item represents a 3 x 3 matrix containing eight
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56 different black and white designs that are logically related and one piece missing at
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58 the bottom right; participants are required to indicate from 8 candidate pieces which
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3 piece completes the matrix. The number of correct items was recorded. All
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5 participants completed the task within 10 minutes.
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8 ***2. Verbal Working memory: Digit span forwards and backwards.***

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10 The 30 digit sequences from the digit span forwards (DSF) and digit span backwards
11 (DSB) subtest of the Wechsler Adult Intelligence Scale—Fourth Edition (WAIS-IV;
12 Wechsler, 2008) were used as a measure of the storage, maintenance, and
13 manipulation components of verbal working memory (Richardson et al., 2011). For
14 presentation consistency the researcher recorded each trial and played the recording
15 via headphones to the participant. Trials began with 2-digit sequences (e.g., 1 – 7) that
16 the participant verbally recalled either forwards or in reverse order (DSF and DSB,
17 respectively). As trials progress the digit sequence gradually increased to nine- (DSF)
18 or eight- (DSB) digits. Testing was terminated if both trials of a number sequence
19 were recalled incorrectly. The number of correct recalls for the DSF and DSB were
20 recorded. The task lasted approximately 7 minutes.
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36 ***3. English receptive vocabulary: British Picture Vocabulary Scale***

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38 The British Picture Vocabulary Scale: Third edition (BPVS-III; Dunn, Dunn, Whetton
39 & Burley, 1997) consists of 14 sets of words that each contains 12 items. Difficulty
40 levels span from simple words understood by 2 – 3 year olds (e.g., ball, Set 1) to
41 vocabulary that is above the level of an average adult (e.g., lacrimation, Set 14). The
42 researcher orally presented the stimulus word and the participant pointed to one of
43 four images that he/she considered most like that word. Children started with Set 8,
44 adults with Set 11. If two or more errors were made on the starting set then the
45 researcher established the base set by going back a set until no more than one error
46 was made. Next, a ceiling set was established by presenting the participant with
47 progressively more difficult sets until 8 or more errors were made on a set. Ability
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3 scores were calculated as the highest number on the ceiling set minus the total number
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5 of errors made during the assessment. Bilingual and monolingual groups were
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7 compared on their ability scores. The task lasted approximately 6 minutes.
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10 11 **Experimental measures**

12 13 14 15 *Metacognition*

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17 The dot discrimination task was programmed and conducted on PsychoPy (version
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19 1.82; Peirce, 2009) and was a shortened version of the task used in Folke et al. (2016)
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21 experiment II. Experimental trials had two phases: 1) First order performance, in
22
23 which all participants had to perform a quick perceptual decision making challenge
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25 and 2) Second order performance, in which they had to rate their confidence in that
26
27 decision. Metacognitive sensitivity reflects the extent that someone's confidence
28
29 rating is predictive of their accuracy in their decision (Fleming & Lau, 2014).
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33 The trial presentation was capped at 2 seconds across the sample. The computation of
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35 metacognitive efficiency (Mratio) is described in the Results section.
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39 Following a training phase (described below) participants completed ten practice
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41 experimental trials and four blocks of 25 experimental trials. For each experimental
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43 trial participants were first presented with the perceptual decision making phase
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45 where they were required to make a quick choice as to whether the circle on the left or
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47 right contained more dots, pressing the corresponding left/right cursor keys on the
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49 keyboard. One circle always contained 50 randomly located dots and the other circle
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51 would contain either fewer or more dots. Two successive correct responses resulted in
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53 the next trial being more difficult (one less dot difference); one incorrect response
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55 resulted in the task getting easier (one more dot difference; the same one-up two-
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57 down staircase procedure used in Fleming, Ryu, Golfinos, & Blackmon 2014). Next,
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3 the metacognitive element of the trial was presented, participants had to rate their
4 confidence that their decision was correct on a sliding scale from 'less' to 'more'
5 confident using the left/right cursor keys to move the pointer and the down cursor key
6 to submit their response. Then a new trial proceeded immediately. The perceptual
7 decision task was response terminated but time limited, failure to respond within 1500
8 ms resulted in a screen stating 'Too slow' appearing for 750 ms and then a new trial
9 was presented. Response time for the confidence judgement was unlimited.

10
11 Before the experimental task participants were asked to view five trials to familiarise
12 them with the stimuli, these were white outlines of a circle on the left and right both
13 containing different numbers of white dots against a black background, beneath each
14 circle was a number informing participants of how many dots were in the circle. Next
15 participants completed a training phase, where they made the quick perceptual
16 decision as to which circle contained the most dots and then feedback appeared
17 underneath the selected circle for 750 ms ('correct' presented in green text or
18 'incorrect' presented in red text, or a new screen stating 'too slow' if they took longer
19 than 1500 ms). The training phase calibrated a participant's difficulty level in the
20 experimental phase. In the first trial of the training phase there was a 20-item dot
21 difference, a correct decision resulted in the dot difference decreasing by four and in
22 subsequent correct trials the difference gradually decreased to one dot difference;
23 incorrect decisions increased the dot difference. Therefore, more difficult trials were
24 those that had a smaller difference of dots contained in the two circles. The training
25 phase ended after participants had switched between correct and incorrect answers
26 eight times. All training trials were excluded from analyses.

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28 The task lasted approximately 12 minutes.
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Measures of executive function

Inhibitory control, monitoring and updating

The Simon task (Simon & Wolf, 1963) was programmed and conducted using E-Prime (version 2.0; Schneider, Eschman, & Zuccoloto, 2007). The task was adapted from Bialystok et al. (2004, study 1). The stimuli consisted of 18 blue stars and 18 red stars randomly presented to the left or right side of a white screen; each colour appeared an equal number of times to the left and right. The ITI was 300, 600, or 900 ms and a fixation cross appeared for 800 ms preceding the stimuli. Participants responded to red stars by pressing the red button on the left (vice versa for a blue stars). During incongruent trials the location of the stimulus and the response button do not match (red star on the right) meaning participants need to inhibit the conflicting spatial information and focus on the colour (i.e., conflict resolution). Congruent trials (red square on the left) do not require conflict resolution meaning participants can respond faster. The task lasted approximately 2 minutes.

Planning and problem solving

The Tower of London task was administered (Shallice, 1982). The task program and software were downloaded from open source Psychology Experiment Building Language (version 0.13; PEBL; <http://pebl.sf.net>), courtesy of Mueller & Piper, 2014). The task consisted of 12 problems. Each problem required participants to use the computer mouse to move coloured discs (red, blue, and green) from their initial position to match their target position in the fewest possible moves. Participants were instructed that only one disc could be moved at a time and also that only the disc on the top of a stack could be moved. A move counter inform them how many moves they could make and how many moves they had left, and there was a maximum space for three discs per stack in the left column, two in the middle, and one in the right.

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3 Participants were also informed that there was no time limit for each problem and
4 they were advised to think about the problem and plan their moves before they
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6 clicked on any discs. Participants clicked on the disc that they wanted to move and
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8 then clicked in the column where they wanted to place the disc. Trials ended when
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10 participants reached the move limit and the screen displayed feedback on whether or
11
12 not they had successfully completed the problem. Participants then clicked to get the
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14 next trial. The initial starting position of the discs remained the same for each trial,
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16 but the target stack altered.
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22 The trials consisted of four easy problems requiring 2-3 moves where the strategy of
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24 moving the coloured discs to match their target location worked and required minimal
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26 planning resources (Shallice, 1982). Four trials were moderate problems requiring 4
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28 moves and initial moves where a disc needed to move away from its target stack (see
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30 Figure 2, where both the red and the green disc need to move away from their target
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32 stack before they can be replaced in the correct order). Four trials were difficult 5-
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34 move problems that required planning multiple sub-goals where as well as discs
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36 initially moving away from their target location, planning was required due to the
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38 middle and right column having restricted space. Trials were presented in a fixed
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40 order where problems gradually increased in difficulty.
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Design

This study had both a between-subject and a mixed-design in which first the developmental trajectories of metacognitive processing and executive function were built across age groups (research questions 1 and 2) and, subsequently, across both age and linguistic group (research question 3). Ability scores were obtained for the background task: BPVS III, Raven's and Digit span and used as covariates in all comparisons. Accuracy and response time scores were calculated the executive function tasks. Mratio was computed for metacognitive efficiency. T-tests, ANOVAs and correlation analyses were performed using SPSS version 25 for Mac. Factor Analysis was performed using the "FactorAnalyzer" package with Python (<https://pypi.org/project/factor-analyzer/>).

Results

Background measures

Independent t-tests showed that the age difference between the language groups (English monolinguals and multilinguals) was non-significant ($t(124) = .12, p = .90$). Statistically equivalent age in monolinguals and bilinguals was also confirmed within each age group ($p = .79, p = .60, p = .50, p = .88$ for childhood, young adulthood, middle adulthood and older adulthood groups, respectively). Age-group scores and comparisons on background tests and socioeconomic status scores between monolingual and multilingual individuals are reported in Table 2. Independent *t*-tests conducted for each age group, indicated that English monolinguals and multilinguals were largely comparable across the measures. However, in some cases, measures of English vocabulary knowledge (BPVS), working memory (digit span backward plus forward) and socio-economic status (averaged composite scores

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3 of parental education, household income, participant higher level of education and
4 employment status) differed significantly. We included these measures as covariates
5 in our initial analyses. However, we conducted further tests to ascertain whether there
6 was a correlation with the experimental measures and whether the covariates and
7 groups were independent. We performed Pearson's correlation analysis including all
8 background and experimental variables, and linear regression analysis for all age
9 groups separately. We observed overall weak correlations with all measures and the
10 regression showed either no correlation or different directions among groups. We
11 concluded that the independence and homogeneity assumptions were violated and
12 therefore decided not to include the background variables as covariates here. The
13 results of the analyses with covariates are reported in the online Supplementary
14 Material II, Table G.

15 Note that the children's SES index is lower than that recorded for the adults. This is
16 due to the fact that two different questionnaires were developed for this study: one for
17 the children (to be completed by their parents) and one for the adults. The adult
18 questionnaire contained two additional questions: 1) Employment status, that is,
19 unemployed, part-time, full-time and retired, and 2) Highest level of education, that
20 is, A-level, Undergraduate, Postgraduate, Doctorate. These questions were not
21 applicable to children and, therefore, excluded.

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3 *How does metacognitive processing and executive function change across the*
4 *lifespan? Are any effects associated with participants' linguistic experience?*

7
8 ***Metacognition***

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10 The results of first order performance, that is, analysis of response times (measured in
11 seconds), accuracy (measured by percentage of correct responses), and the difficulty
12 of the trials (measured by dot difference) across all age groups and linguistic groups
13 are reported in the online Supplementary Material III.

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19 ***Second order performance: metacognitive efficiency***

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21 To estimate metacognitive efficiency we used the Mratio. An Mratio was fitted to
22 each participant's data using a hierarchical Bayesian estimation method (see Folke et
23 al., 2016 for a more detailed description - MATLAB code available at
24 <https://github.com/smfleming/HMM>). The Mratio scores for all age and language
25 groups are reported in Table 3 and illustrated in Figure 1.

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34 --- Insert Table 3 about here ---

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38 ANOVA showed a trend main effect of age group, $F(3,322)=2.13$, $p=.096$, $\eta_p^2=.02$.
39 There was no significant effect of language group, $F(1,322)=.031$, $p=.86$, $\eta_p^2<.001$,
40 nor a significant interaction between age and language groups, $F(3,322)=.14$, $p=.94$,
41 $\eta_p^2=.001$.

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50 Overall, better metacognitive performance was observed in middle-adulthood (mean
51 = 1.12) than all the other groups, but the differences between the groups were not
52 statistically significant ($p>.10$).

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59 --- Insert Figure 1 about here ---
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3 In summary, metacognitive efficiency expressed by M_{ratio} , showed a consistent trend
4 across all ages, with improvement through development, best performance in middle-
5 age and progressive decline in older age. Linguistic experience did not have any
6 significant effect on metacognitive processing, that is, monolingual and multilingual
7 speakers had comparable performance across all ages. Bayesian independent t-tests
8 comparing metacognitive efficiency across linguistic groups in each age group
9 indicated that the data were more than three times less likely to occur under the
10 alternative hypothesis than the null hypothesis in all comparisons ($BF^{10} < .32$).
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23 ***Executive Function: Inhibition and control***

24 Response time and accuracy scores for congruent and incongruent trials in the Simon
25 task are reported in the online Supplementary Material I, Table B and C, and
26 illustrated in Figure 2 below.
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31 For response time, a three-way ANOVA for age groups (childhood, young adulthood, mid-
32 adulthood and older adulthood), language groups (monolinguals, multilinguals) and
33 congruency (congruent, incongruent) revealed a highly significant main effect of congruency
34 overall, $F(1,322)=464.7, p<.001, \eta_p^2=.59$. The interaction between congruency and age group
35 on response time was significant, $F(3,322)=9.0, p<.001, \eta_p^2=.08$, but not for language groups,
36 $F(1,322)=.58, p=.45, \eta_p^2=.002$. The interaction between age and language groups was also
37 non-significant, $F(3,322)=.22, p=.85, \eta_p^2<.001$. There was a significant overall main effect of
38 age group, $F(3,322)=78.47, p<.001, \eta_p^2=.42$, but the main effect of language groups and the
39 interaction between age and language groups were both not significant ($p=.89$).
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50 Bonferroni adjusted pair-wise comparisons (Figure 5), showed that young adults were
51 significantly the fastest compared to children, -159 ms, middle-aged adults -51 ms
52 and older adults, -132 ms ($p<.001, p=.005$ and $p<.001$, respectively). Performance in
53 middle-adulthood was significantly better than in childhood and in older adulthood
54 (mean difference = -107, $p<.001$, mean difference -81 ms, $p<.001$, respectively). The
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3 older adults' performance was comparable with children's (mean difference = -26 ms,
4 $p=.26$). In summary, a developmental analysis of response time in the Simon task
5
6 revealed a peak in best performance with both congruent and incongruent trials in
7
8 young adults. As expected, performance was worse in childhood and declined in older
9
10 age. The difference in linguistic experience between individuals in all age groups did
11
12 not produce any statistically significant effect ($p=.85$).
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24 The same three-way ANOVA with accuracy scores again revealed a significant main
25 effect of congruency, $F(1,322)=89.64$, $p<.001$, $\eta_p^2=.22$, indicating more correct
26 responses with congruent trials, and a significant main effect of age group,
27
28 $F(3,322)=24.64$, $p<.001$, $\eta_p^2=.19$. However, there was a non-significant effect of
29 language group, $F(1,322)=.46$, $p=.50$, $\eta_p^2=.001$. The interaction between congruency
30 and age group was highly significant, $F(3,322)=11.41$, $p<.001$, $\eta_p^2=.10$. All the other
31 interactions, that is, congruency*language group, age group*language group and
32 congruency*age group*language group were non-significant ($p=.73$, $p=.65$, $p=.87$,
33 respectively).
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44 Bonferroni adjusted pair-wise comparisons (Figure 3), showed that young adults were
45 significantly more accurate than children (mean difference = 7.6%, $p<.001$), but their
46 performance did not differ from that of middle-adulthood and older participants
47 ($p=1.0$ and $p=.13$, respectively). The middle-aged adults' and older adults'
48 performance compared with childhood were also significantly different (mean
49 difference = 7.4%, $p<.001$, 4.6%, $p=.001$, respectively). A 2.8% difference in
50 accuracy between middle-adulthood and older adulthood was not significant ($p=.43$).
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3 As observed in the RT analysis above, the difference in linguistic experience between
4 individuals in all age groups for accuracy in both trial conditions did not produce any
5 statistically significant effect. Bayesian independent t-tests comparing Simon accuracy
6 and RT across linguistic groups on congruent and incongruent trials conducted
7 separately for each age group indicated that the data were more than three times less
8 likely to occur under the alternative hypothesis than the null hypothesis in all
9 comparisons ($BF^{10} < .34$).

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26 To summarise, a developmental analysis of accuracy in the Simon task revealed a
27 peak in best performance with both congruent and incongruent trials in young adults.
28 Children had worse performance compared to the other groups, and the difference in
29 linguistic experience between individuals in all age groups did not produce any
30 significant effect.

31 ***Simon cost***

32 The response time difference between congruent and incongruent trials (Simon cost)
33 was computed for all participants across all age groups and analysed with an
34 ANOVA. There was a highly significant main effect of age group, $F(3,322)= 9.0$,
35 $p<.001$, $\eta_p^2=.07$. There was a non-significant main effect of language group,
36 $F(1,322)=.58$, $p=.45$, $\eta_p^2=.002$, and the interaction between age and language groups
37 was also non-significant, $F(3,322)=.26$, $p=.86$, $\eta_p^2=.002$. Bayesian independent t-tests
38 comparing Simon cost across linguistic groups separately for each age group
39 indicated that the data were more than five times less likely to occur under the
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3 alternative hypothesis than the null hypothesis in children ($BF^{10} = .17$) and more than
4
5 two times less likely in all adult groups ($BF^{10} < .35$ in all cases).
6

7
8 Bonferroni adjusted pair-wise comparisons, showed that young adults had a smaller
9
10 Simon cost than children, -27 ms and older adults, -41 ms ($p=.001$ and $p<.001$,
11
12 respectively), but their performance was comparable with middle-adulthood (-17 ms,
13
14 $p=.32$). Performance in middle-adulthood was significantly better than in childhood
15
16 and in older adulthood (mean difference = -107, $p<.001$, mean difference -81 ms ,
17
18 $p<.001$, respectively). In summary, a developmental analysis of the Simon cost, again
19
20 revealed a peak in best performance in young adults. There were no significant
21
22 statistical differences among the other age groups ($p>.05$ in all cases). The difference
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24 in linguistic experience between individuals in all age groups did not produce any
25
26 statistically significant effect ($p>.45$ in all cases).
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33 ***Executive Function: Planning***

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35 Overall accuracy, overall response time and response time to initiate the first move on
36
37 the Tower of London test were analysed by age and language group. Trials were split
38
39 in two categories according to level of complexity: 1) *moderate* (2 and 3 moves) and
40
41 2) *challenging* (4 and 5 moves). The rationale for this division is based on previous
42
43 findings in bilingual research showing that multilingual speakers outperformed
44
45 monolinguals only when the task presented an extra level of complexity (e.g., Filippi
46
47 et al., 2012; Filippi et al., 2015). Means and standard deviations are reported in the
48
49 online Supplementary Material I, Tables D, E and F.
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53 The three-way ANOVA for accuracy scores revealed an overall significant main
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55 effect of trial complexity, $F(1,322)=271.29$, $p<.001$, $\eta_p^2=.46$. The interaction between
56
57 complexity and age group was significant, $F(3,322)=2.75$, $p=.043$, $\eta_p^2=.025$.
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3 The two-way interactions between trial complexity and language group and the three
4
5 way interaction between complexity, age group and language group were all non-
6
7 significant ($F(1,322)=.46, p=.50, \eta_p^2=.001$, and $F(3,322)=.27, p=.85, \eta_p^2=.002$,
8
9 respectively).

10
11 Tests of between subjects showed a significant main effect of age group,
12
13 $F(3,322)=35.0, p<.001, \eta_p^2=.25$, but the main effect of language groups and the
14
15 interaction between age and language groups were both not significant ($p=.40$ and
16
17 $p=.50$, respectively).

18
19 Bonferroni corrected pair-wise comparisons (Figure 4), showed and that children
20
21 were significantly less accurate than the other age group (average mean difference =
22
23 difference=18.7%, $p<.001$). All other groups had comparable performance ($p>.60$).
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26
27 In summary, a developmental analysis of accuracy in the Tower of London task
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29 revealed a comparable performance in all age groups, with the exception of children
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31 who performed significantly worse than adults overall.
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35 There was no effect of linguistic experience: monolinguals and multilinguals in all age groups
36
37 had similar performance ($p>.40$). Bayesian independent t-tests comparing overall
38
39 accuracy performance across linguistic groups in each age group indicated that the
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41 data were more than five times less likely to occur under the alternative hypothesis
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43 than the null hypothesis in the childhood group ($BF^{10} < .19$), more than four times
44
45 less likely in the middle adulthood ($BF^{10} < .25$), more than three times less likely in
46
47 the middle adulthood group ($BF^{10} < .32$) and more than 1.6 times less likely among
48
49 the older participants ($BF^{10} < .74$).
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3 ANOVA for overall mean response time to complete the test showed a significant
4 main effect of task complexity, $F(1,322)=156.59, p<.001, \eta_p^2=.33$, and significant
5 main effects of age group and language group, $F(3,322)=9.94, p<.001, \eta_p^2=.085$,
6 $F(1,322)=7.05, p=.008, \eta_p^2=.021$, respectively. There was a significant interaction
7 between complexity and age group, $F(3,322)=5.69, p=.001, \eta_p^2=.050$, but all other
8 interactions were non-significant ($p>.30$).
9

10
11 Bonferroni corrected pair-wise comparisons (Figure 5), showed and that older adults
12 were significantly slower than children (mean difference = 7.5 seconds, $p<.001$) and
13 young adults (mean difference = 7.3 seconds, $p<.001$), but their performance was
14 comparable with the middle-aged group ($p=.40$). Monolinguals were overall 3.1
15 seconds faster than multilinguals in completing the task ($p=.008$). This difference was
16 particularly evident and statistically significant in young adults for both moderate and
17 challenging trials (Mean difference = 5.5 seconds, $t(69.8)=-3.16, p=.002$; Mean
18 difference = 6.3 seconds, $t(63.1)=-2.70, p=.009$, respectively). Bayes factors
19 confirmed that, in young adults, the alternative hypothesis for the linguistic group
20 effect was over 22 times more likely under the alternative hypothesis for overall RT
21 ($BF^{10} = 22.57$), a figure far lower for children ($BF^{10} = 0.26$), middle adults ($BF^{10} =$
22 0.31) and older adults ($BF^{10} = 0.41$).
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51 The final ANOVA was carried out on the mean response time taken to plan the first
52 move for both *moderate* and *challenging* trials. There was an overall significant effect
53 of trial complexity, $F(1,322)=49.55, p<.001, \eta_p^2=.133$, a significant main effect of age
54 group, $F(3,322)=13.01, p<.001, \eta_p^2=.108$, and language group, $F(1,322)=7.38$,
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3 $p=.007$, $\eta_p^2=.022$. The two-way interaction between trial complexity and age group
4 was highly significant, $F(3,322)=7.67$, $p<.001$, $\eta_p^2=.067$ but all other interactions
5 were non-significant ($p>.20$).
6
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10 Bonferroni corrected pair-wise comparisons (Figure 6), showed that children were
11 significantly faster than young adults (mean difference = 3.4 seconds, $p=.010$),
12 middle-adults (mean difference = 5.5 seconds, $p<.001$) and older adults (mean
13 difference = 6.8 seconds, $p<.001$). The other groups' performance was comparable
14 ($p>.10$).
15
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19 Monolinguals were, on average, 2.6 seconds faster than multilinguals in planning the
20 first move. Consistent with overall RT, the difference was statistically significant in
21 young adults for both moderate and challenging trials (Mean difference = 5.0 seconds,
22 $t(76)=-2.84$, $p=.006$; Mean difference = 6.3 seconds, $t(61.5)=-2.75$, $p=.008$,
23 respectively). Bayesian analysis confirmed this considerable linguistic group effect in
24 young adults, with the alternative hypothesis more than 20 times more likely than the
25 null hypothesis ($BF^{10} = 20.09$), an effect absent in the other age groups ($BF^{10} < .41$ in
26 all cases).
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47 To summarise the overall results from the Tower of London task, it was observed that
48 the response time for both the execution of the whole task and for planning the first
49 move in each trial worsen with age. However, adults were more accurate: all adult age
50 groups outperformed children in providing the right solution, irrespective of trial
51 complexity.
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3 *Is metacognition associated with executive function across the lifespan?*
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6 Nine variables were factor-analysed across all groups with varimax (orthogonal)
7
8 rotation. The Bartlett sphericity ($p < .001$) and Kaiser-Meyer-Olkin ($KMO = .781$)
9
10 measures verified the sampling adequacy for the analysis. The analysis yielded three
11
12 factors with Eigenvalues higher than 1 explaining a total of 52.65% of the variance
13
14 for the entire set of variables. Table 4 shows the factor loadings after rotation.
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19 --- *Insert Table 4 about here* ---
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24 Factor 1 showed higher loadings toward more difficult tasks, i.e., challenging trials in
25
26 the Tower of London and, to a lesser extent, incongruent trials in the Simon task.
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29 Performance on digit span and Raven's matrices also loaded highly, indicative of a
30
31 shared latent executive function/fluid intelligence factor underpinning performance on
32
33 these tasks. This first factor explained 20.87% of the variance.
34

35
36 Factor 2 was mainly represented by the Simon task with congruent and incongruent
37
38 trial response time. This factor may represent both sustained attention to the task and
39
40 inhibitory control or conflict monitoring. Factor 2 explained 20.65% of the variance.
41

42
43 The third factor was uniquely represented by the metacognition task explaining
44
45 11.16% of the variance.
46

47
48 Two separate exploratory factor analyses were carried out for children and for adults.

49
50 The results were largely consistent with our full sample findings (see Figures 7 and 8
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52 below). Rotated matrices are reported in the online Supplementary Material IV.
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56 --- *Insert Figure 7 about here* ---
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59 --- *Insert Figure 8 about here* ---
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5 Overall, factor analysis has shown that metacognitive processing does not appear to
6 recruit the same mechanism associated with performance on the tests of working
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10 memory, fluid intelligence and executive function.
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Discussion

Our primary objective in this study was to chart the developmental trajectories of performance on measures of metacognitive processing and executive function across the life span. For this purpose a large sample of healthy individuals (N=330) from 7 to 80 years old were tested on the same tasks measuring executive function (inhibitory control, conflict monitoring and updating and strategic planning), working memory, fluid intelligence and metacognition. A second objective was to identify the relationship between metacognition and executive function and consider how this relationship changes across the lifespan. Finally, in order to address the viability of the bilingual cognitive advantage hypothesis, we determined whether the trajectory of these effects is modulated by participants' linguistic experience.

Developmental trajectories of metacognitive processing

We administered a two-alternative-forced-choice task in which participants attempted to identify which one of two circles presented on screen contained more dots (within a 2 second response window) and subsequently rate their level of confidence in their choice. Metacognitive efficiency was computed and expressed by M_{ratio} (Barrett, Dienes & Seth, 2013; Fleming & Lau, 2014) and compared across the four age groups. The developmental trajectory showed that participants in the middle-adulthood group (36-55 years old) demonstrated best metacognitive efficiency, that is, they tended to feel more confident in trials they completed correctly and less confident in trials where their performance was not correct. The childhood group (7-12 years old) showed overall worst metacognitive performance. A steep metacognitive efficiency decline was observed in older age (56-80 years old).

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3 Participants' linguistic experience did not produce any significant effect: both
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5 monolingual and multilingual speakers' trajectories were comparable overall.
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7 This result is inconsistent with a study by Folke et al. (2016), which employed the
8
9 same task but reported a metacognitive disadvantage in multilingual young adults in
10
11 comparison to monolingual peers. Beyond the more constrained age range, the most
12
13 evident difference between that study and the present one is that, of the 31 bilinguals,
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15 just over half did not begin learning a second language until after the age of 6. In our
16
17 present study which included a group of 78 young adults, all 165 multilingual
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19 participants were simultaneous bilinguals, exposed to two or more language from
20
21 birth. Metacognitive processing in bilingualism is a new area of research, and it is
22
23 therefore not possible to draw firm conclusions regarding the relevance of
24
25 bilingualism to the development of metacognitive efficiency. Nevertheless, in
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27 supporting either a disadvantage or no advantage at all, these studies together (which,
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29 to our knowledge, are the only studies to date focusing on metacognition in bilingual
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31 research using this method) are most consistent with the position that bilingualism
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33 does not confer benefit in this regard: there is no general metacognitive bilingual
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35 advantage.
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42 *Developmental trajectories of executive function and planning*

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44 The Simon task was used to measure executive function across the lifespan.
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46 Consistent with previous work (for a review see Van der Lubbe & Verleger, 2002),
47
48 the developmental trajectory showed the best reaction time performance in young
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50 adults when compared with the other age groups. Older adults showed a significant
51
52 decline both in terms of response time and accuracy, especially on incongruent trials.
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54 This result is in line with previous research showing a progressive improvement of
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56 inhibitory control and monitoring in childhood and young-adulthood, and a decline
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3 associated with ageing (e.g., De Luca et al., 2003; De Luca & Leventer, 2010;
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5 Hämmerer et al., 2010; Lorscheid & Reimer, 2008; Rabbitt et al., 2001).
6
7 Nevertheless, contrary to previous psycholinguistic research (e.g., Bialystok et al.
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9 2004), there was no significant effect of multilingualism across the lifespan. The
10
11 development and decline of inhibitory control and monitoring followed the same
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13 trajectory in both monolingual and multilingual speakers. However, although the
14
15 Simon test is widely employed as a measure of inhibition, we also acknowledge that
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17 reported correlations of performance across tests designed to measure inhibition are
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19 frequently low, and that this observation has led authors to question the convergent
20
21 validity of the term, and therefore its usefulness in the literature (e.g., Paap, Anders-
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23 Jefferon, Zimiga, Mason, & Mikulinsky, 2020; Rey-Mermet, Gade, & Oberauer,
24
25 2018).

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33 On the Tower of London task, designed to assess strategic executive function and
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35 planning, all groups showed comparable accuracy performance (trials successfully
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37 completed) when the demand of the task was less challenging, that is, with trials
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39 requiring fewer moves to completion. However, the trajectory was different when the
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41 trials placed greater demands on strategic planning. Young adults had best
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43 performance and a progressive decline was observed with ageing, especially in the
44
45 multilingual population, although the difference was not statistically significant.
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47 Developmental trajectories of response time revealed a different pattern, in which
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49 monolingual speakers in general, and especially in young-adulthood, showed
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51 significantly faster overall performance in completing the task than multilingual peers
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53 in all age groups. This difference was particularly significant when the time to
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55 perform the first move was considered. English monolingual young-adults
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3 demonstrated a faster response time with planning than multilingual peers both for
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5 less demanding and more challenging trials. These findings are consistent with a
6
7 study of 45 young adults by Naeem et al. (2018), in which monolinguals were also
8
9 found to perform better on the Tower of London test, once socioeconomic status of
10
11 participants was taken into account. Another recent study by Papageorgiou et al.
12
13 (2019) in older participants showed statistically equivalent performance in
14
15 monolinguals and bilinguals, with a trend towards a bilingual disadvantage in
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17 response times on this task. Together these findings clearly do not support the
18
19 existence of a genuine cognitive advantage in executive function which is
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21 underpinned by multilanguage acquisition. To the extent that there is a bilingual
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23 advantage, it appears not to extend to planning and sustained cognitive control of
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25 behavior towards a goal.
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33 *Links between metacognition and executive function*

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35 Exploratory factor analysis is a statistical method designed to identify latent factors or
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37 constructs that contribute to performance across multiple variables entered into the
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39 model. The results presented here clearly indicate that metacognitive efficiency (as
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41 measured by Mratio) is independent of the mechanism(s) driving performance on our
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43 other tasks. We identified strong correlations between Raven's matrices, digit span
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45 and Tower of London performance and Factor 1, indicating that a working
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47 memory/executive attention construct underpins performance on these tests. Response
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49 times for both congruent and incongruent trials on the Simon test loaded strongly on a
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51 second factor. The key finding, however, was that our measure of metacognition
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53 showed a negligible correlation with factors 1 and 2 and instead independently loaded
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55 on the third extracted factor in our full sample. Over 99% of the variance in our
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3 metacognition variable was unique, indicating that virtually zero variance was shared
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5 with the other variables in our model. This finding is consistent with studies of
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7 confidence judgements on fluid intelligence tasks (e.g., Stankov, 2000) metacognitive
8
9 efficiency in the domains of memory and perception (Palmer et al., 2014), but not
10
11 with studies employing ‘feeling of knowing’ (Souchay, Isingrini, Clarys, Taconnat, &
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13 Eustache, 2004), raising the possibility that there may be different forms of
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15 metacognitive processing of which only some share the same cognitive mechanisms
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17 underpinning executive function. Nevertheless, on the basis of the present findings
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19 we conclude that perceptual metacognitive efficiency relies on mechanisms distinct
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21 from those serving working memory and executive planning abilities. As outlined in
22
23 our Introduction we suggest that the balance of evidence in the literature is most
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25 consistent with there being a domain general metacognitive ability in older children
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27 and adults, which is drawn upon irrespective of task characteristics, and we therefore
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29 hypothesise that cognitive mechanisms underpinning metacognitive skills may be
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31 quite independent from those serving executive function/cognitive control beyond the
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33 domain of perception-based discrimination performance. However, further research,
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35 undertaken with a diverse range of metacognitive tasks, is required to formally
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37 address this question. We also encourage efforts to address the developmental
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39 trajectories of these cognitive systems in children.
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49 *The effects of multilingualism on metacognition and executive function across the*
50 *lifespan*
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53 Across the tests presented in the current study comparable levels of performance were
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55 observed in monolingual and bilingual groups, and this finding applied in all age
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57 groups (although it should be noted that numbers of participants in our older age
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3 groups were comparatively small). The only significant effect favoured monolingual
4 participants, who performed the Tower of London task faster than multilinguals
5 (particularly the case in the younger age groups). However, the level of accuracy was
6 comparable in both linguistic groups and across all ages. The evidence base for the
7 bilingual cognitive advantage (Bialystok, 2018) has been robustly challenged in the
8 recent literature on bilingualism (e.g., de Bruin et al., 2015; Goldsmith & Morton,
9 2018; Paap et al., 2015) and the present findings are also incompatible with the
10 primary claim of this theory: that the process of becoming bi/multilingual confers
11 domain general benefits in executive function and cognitive control. Our present
12 findings, based on a considerably larger sample than that typically employed in
13 bilingualism research, provide further confirmatory evidence not only that there is no
14 statistically meaningful advantage for bilinguals on widely established tests of
15 executive function, but also that bilingualism does not appear to offer advantages in
16 metacognitive efficiency.
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37 *Conclusions*

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39 Our findings indicate that metacognitive efficiency and accuracy on measures of
40 executive function show similar, non-linear trajectories across the lifespan, with
41 children performing disproportionately worse than young and middle-aged adults, and
42 older adults showing a marked decline. However, despite these trends, there was no
43 statistical evidence for a relationship between metacognition and our sampled
44 components of executive function (strategic planning, fluid intelligence, conflict
45 monitoring and working memory) indicating that these broad cognitive abilities may
46 be served by independent cognitive mechanisms. Our findings, based on carefully
47 matched groups of participants, also indicate that bilingualism does not appear to
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3 confer advantages either in executive function or metacognition in children (over the
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5 age of 6) or adults of any age.
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12 **Supplementary Material**
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14 The Supplementary Material is available at: qjep.sagepub.com
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Figure Captions

Figure 1: Metacognition task, second order performance. Developmental trajectories of metacognitive efficiency (mean M_{ratios}) with a comparison between age and language groups. Error bars show standard error.

Figure 2: Simon task effects - Developmental trajectories of mean response time in for congruent and incongruent trials, with a comparison between age and language groups. Error bars show standard error.

Figure 3: Simon task effects - Developmental trajectories of mean correct responses, with a comparison between age and language groups. Error bars show standard error.

Figure 4: Developmental trajectories of mean correct responses in the Tower of London task, with a comparison between age and language groups. Error bars show standard error.

Figure 5: Developmental trajectories of overall mean response time for the execution of the Tower of London task (12 trials), with a comparison between age and language groups. Error bars show standard error.

Figure 6: Developmental trajectories of mean response time in planning the first move in the Tower of London task, with a comparison between age and language groups. Error bars show standard error.

Figure 7: Exploratory factor analysis for children.

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Figure 8: Exploratory factor analysis for adults.

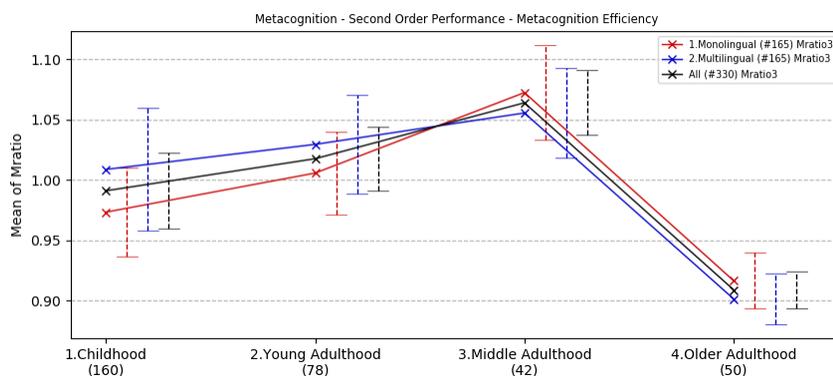


Figure 1: Metacognition task, second order performance. Developmental trajectories of metacognitive efficiency (mean Mratios) with a comparison between age and language groups. Error bars show standard error.

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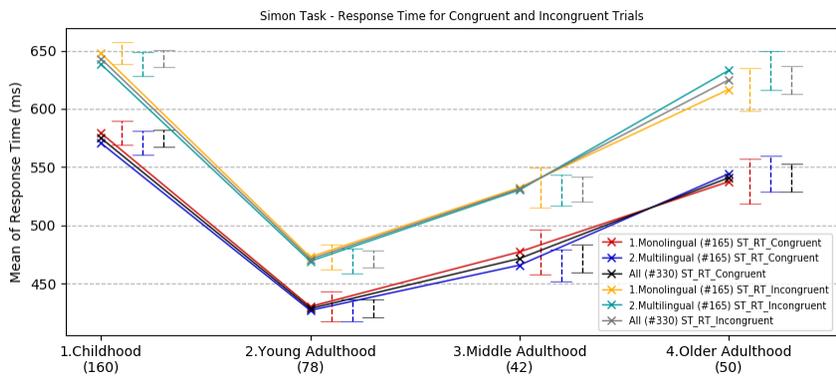


Figure 2: Simon task effects - Developmental trajectories of mean response time in for congruent and incongruent trials, with a comparison between age and language groups. Error bars show standard error.

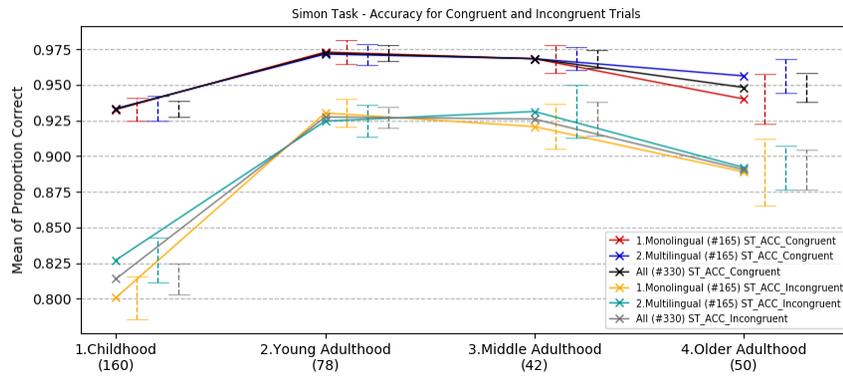


Figure 3: Simon task effects - Developmental trajectories of mean correct responses, with a comparison between age and language groups. Error bars show standard error.

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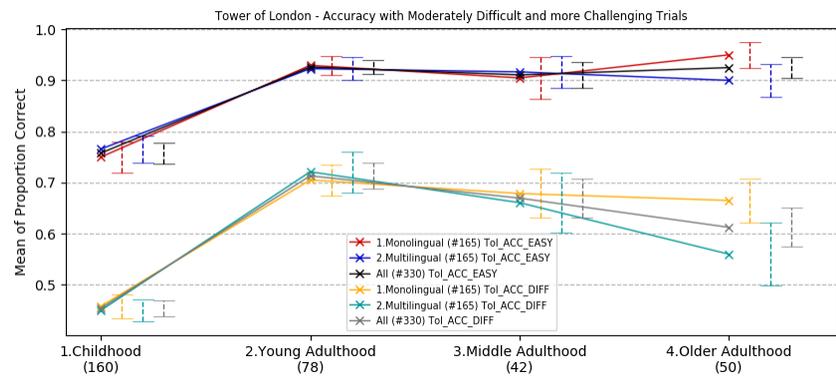


Figure 4: Developmental trajectories of mean correct responses in the Tower of London task, with a comparison between age and language groups. Error bars show standard error.

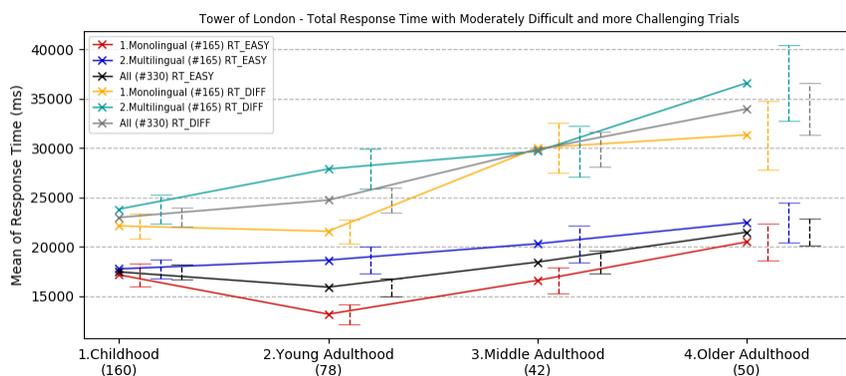


Figure 5: Developmental trajectories of overall mean response time for the execution of the Tower of London task (12 trials), with a comparison between age and language groups. Error bars show standard error.

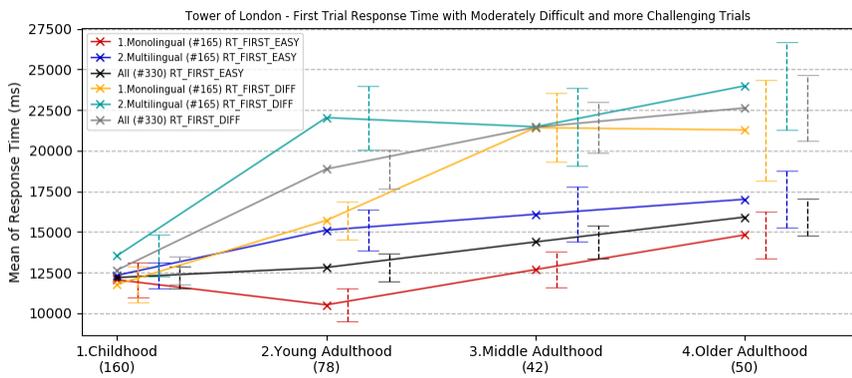


Figure 6: Developmental trajectories of mean response time in planning the first move in the Tower of London task, with a comparison between age and language groups. Error bars show standard error.

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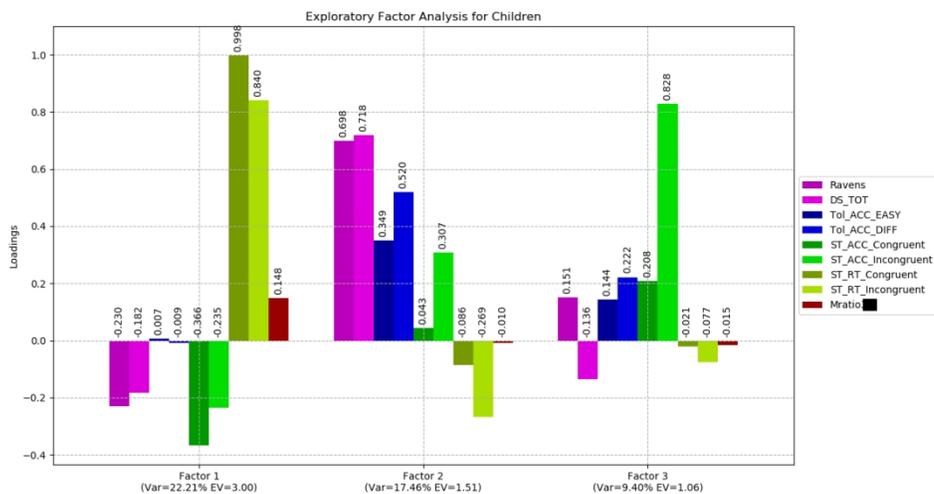


Figure 7: Exploratory factor analysis for children.

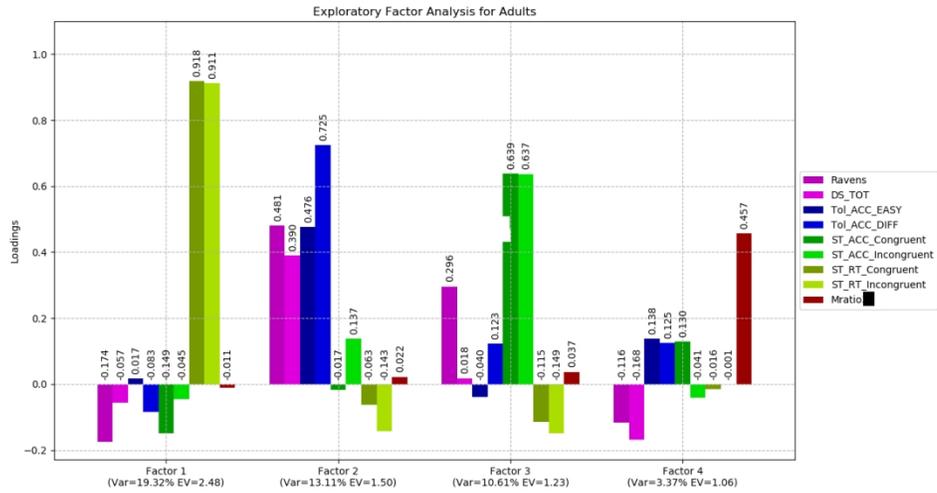


Figure 8: Exploratory factor analysis for adults.

Table 1: Total number of participants separately by age group (in years) and linguistic group. Standard deviations are in brackets.

Age Groups	Total	Mean age	Monolinguals	Mean age	Multilinguals	Mean age
<i>Children</i>						
7-12 years	160	9.4(1.3)	80	9.4(1.3)	80	9.4(1.4)
<i>Young Adults</i>						
18-35 years	78	25.3(4.4)	39	25.6(4.2)	39	25.1(4.7)
<i>Middle age Adults</i>						
36-55 years	42	43.9(5.9)	21	44.5(6.0)	21	43.3(5.5)
<i>Older Adults</i>						
56-80 years	50	68.1 (6.0)	25	68.2 (4.7)	25	68.0(7.1)

Table 2: Age and linguistic groups ability scores for non-verbal reasoning (Raven's), English vocabulary knowledge (BPVS), short-term and working memory, digit span forward and backward, and socio-economic status. Standard deviations in brackets. Independent *t*-tests conducted by age group compare monolinguals with multilinguals differences. Statistically significant results are reported in bold.

Age Group	Measure	All	Monolinguals	Multilinguals	<i>p</i>
Childhood 7-12 years	Raven's	6.6(2.6)	6.7 (2.6)	6.5(2.6)	<i>p</i> =.67
	BPVS	130.9(18.0)	132.3(16.3)	129.1(19.4)	<i>p</i> =.33
	Digit Span Forward	8.5(1.7)	8.4(1.5)	8.5(1.8)	<i>p</i> =.61
	Digit Span Backward	5.2 (1.9)	5.4 (1.9)	5.3 (2.0)	<i>p</i> =.47
	Digit Span Total	13.6(3.2)	13.4(3.0)	13.8(3.7)	<i>p</i> =.48
	Socio-Economic status	5.3(1.1)	5.1(1.2)	5.5(1.0)	<i>p</i>=.04*
Young Adulthood 18-35 years	Raven's	9.9(2.2)	9.8(2.2)	10.1(2.2)	<i>p</i> =.57
	BPVS	160.1(6.8)	162.8(5.9)	157.3(6.6)	<i>p</i><.001
	Digit Span Forward	10.8(2.3)	10.9(2.4)	10.8(2.1)	<i>p</i> =.81
	Digit Span Backward	8.0 (2.6)	7.8 (2.7)	8.2 (2.5)	<i>p</i> =.51
	Digit Span Total	18.9(4.5)	18.7(4.7)	19.0(4.2)	<i>p</i> =.80
	Socio-Economic status	6.9(1.1)	6.8(1.1)	6.10(1.0)	<i>p</i> =.43
Middle Adulthood 36-55 years	Raven's	9.6(1.7)	10.1(1.9)	9.2(1.6)	<i>p</i> =.14
	BPVS	162.3(6.1)	165.1(2.1)	159.6(7.6)	<i>p</i>=.003
	Digit Span Forward	10.9(2.6)	12.0(2.3)	9.9(1.9)	<i>p</i>=.004
	Digit Span Backward	8.6(2.6)	9.3 (2.9)	7.7 (2.2)	<i>p</i>=.04
	Digit Span Total	19.4(4.3)	21.3(4.4)	17.6(4.3)	<i>p</i>=.007
	Socio-Economic status	6.7(1.4)	6.2(1.6)	7.2(1.1)	<i>p</i>=.03
Older Adulthood 56-80 years	Raven's	8.6(2.4)	9.2(1.8)	8.0(2.8)	<i>p</i> =.10
	BPVS	166.1(2.3)	166.0(2.9)	166.3(1.7)	<i>p</i> =.64
	Digit Span Forward	11.3(2.4)	11.2(2.4)	11.5(2.4)	<i>p</i> =.69
	Digit Span Backward	8.1(2.3)	8.2 (2.1)	8.0 (2.5)	<i>p</i> =.72
	Digit Span Total	19.4(4.3)	19.4(4.2)	19.5(4.4)	<i>p</i> =.97
	Socio-Economic status	6.0(1.5)	5.6(1.3)	6.6(1.6)	<i>p</i>=.02

* Where equal variances was not assumed the corrected *p* value was used.

Table 3: Metacognition task, second order performance. Mratio scores and standard deviations (in brackets). An Mratio of zero indicates that confidence judgements hold zero metacognitive sensitivity to the perceptual discrimination (first order) performance, with an MRatio of 1 indicating optimal metacognitive sensitivity. An MRatio value greater than 1 indicates that these participants have drawn on some other information, such as hunches (e.g., Scott et al., 2014) or knowledge of additional factors associated with task stimuli and/or performance when making their confidence judgements (Fleming, 2017, Fleming & Daw, 2017).

Age Group	All Participants	Monolinguals	Multilinguals
Childhood	0.99 (0.40)	0.97 (0.33)	1.01 (0.45)
Young Adulthood	1.01 (0.23)	1.01 (0.21)	1.03 (0.26)
Middle Adulthood	1.06 (0.17)	1.07 (0.18)	1.05 (0.17)
Older Adulthood	0.91 (0.11)	0.92 (0.12)	0.90 (0.10)

Table 4: Factor analysis with varimax rotation across all groups.

	Loadings		
	Factor 1	Factor 2	Factor 3
Fluid Intelligence (Ravens)	0.666	-0.271	-0.037
Working Memory (digit span backward+forward)	0.653	-0.25	0.015
Tower of London: Accuracy Moderate Trials	0.511	-0.064	-0.027
Tower of London: Accuracy Challenging Trials	0.671	-0.128	0.034
Simon task: Accuracy congruent Trials	0.096	-0.304	0.057
Simon task: Accuracy incongruent Trials	0.353	-0.154	-0.031
Simon task: Response Time Congruent Trials	-0.217	0.958	0.039
Simon task: Response Time Incongruent Trials	-0.341	0.814	0.047
Metacognition (Mratio)	-0.008	0.037	0.997
<i>Eigenvalues</i>	<i>3.71</i>	<i>1.20</i>	<i>1.04</i>
<i>Percent of Total Variance</i>	<i>20.87%</i>	<i>20.62%</i>	<i>11.16%</i>
<i>Cumulative Variance</i>	<i>52.65%</i>		