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Abstract

Divergent and convergent creativity may rely on associative and executive control processes. We examined whether age-related differences in both types of creativity are mediated by executive functions and associative processes. A total of 427 primary, secondary-school, and university students completed a battery of tasks measuring executive functioning (updating, inhibition and shifting), verbal fluency, and divergent (fluency, flexibility, and originality) and convergent creativity (remote-associative problems). The results confirmed that executive and associative processes accounted for age-related differences in divergent and convergent creativity, albeit to different degrees. Specifically, verbal fluency contributed to explaining age differences in both types of creativity, whereas updating and inhibition mediated age-related differences only in convergent creativity. These findings provide evidence for the differential contribution of executive and associative processes to age-differences in both types of creativity, and provide additional support for a dual-process view of creativity.

Keywords: age-related differences, divergent creativity, convergent creativity, executive functions, associative processes

Age-Related Differences in Creative Cognition: The Mediating Role of Executive Functions and Associative Processes

Creativity appears to increase with age during childhood and adolescence, although the factors underlying the age-related improvement in creative behavior remains to be understood. Creative problem solving involves the generation of novel responses and entails a complex process in which innovative ideas and solutions are generated in both usual and unusual complex situations (Runco, 2007). Since Guilford's (1967) seminal work, a fundamental distinction between divergent and convergent thinking has been drawn. Divergent thinking implies generating a wide range of solutions or ideas in response to a specific stimulus, with the number of responses, their variety, as well as their originality or rarity being the most relevant features (Guilford, 1967; Runco, 2007), whereas convergent thinking involves the search for a single, correct solution, to a given problem (Brophy, 2001; Guilford, 1967). Neurocognitive and behavioral evidence suggests that the processes underlying both types of creative processing are different (see Zhang et al., 2020, for a review).

Classical theories of creative cognition advocated for a differentiation between two processing modes: controlled vs. automatic. Wallach and Kogan (1965) suggested that attentional control processes are involved in deducing single solutions and that associative processes are involved in idea generation (see also Mednick, 1962). More recently, the dual-processes view represents an integrated approach that posits that creative thinking encompasses a combination of associative and controlled-attention processes (Barr, et al., 2015; Beaty et al., 2014; Benedek & Jauk, 2018; Dygert & Jarosz, 2020; Gilhooly & Fioratou, 2009; Lee & Therriault, 2013). Existing research provides evidence of the involvement of both types of processes in each type of creativity. For instance, Lee and Therriault (2013) revealed that associative fluency is a fundamental factor influencing both divergent and convergent thinking processes. Similarly, several studies reported positive correlations between working memory and divergent (e.g., Benedek et al., 2014) as well as convergent (e.g., Chuderski & Jastrzębski, 2018) thinking measures. Neuroimaging research has also offered support for the view of dual processes in divergent thinking (see Volle, 2018).

Although both associative and executive processes may play a role in both types of creative thinking, their degree of involvement can vary. For instance, updating might be more relevant to convergent than to divergent thinking (Benedek et al., 2014); whereas associative processes, assessed through verbal fluency, may play a more important role in divergent thinking compared to convergent thinking (Dygert & Jarosz, 2020). Research has predominantly focused on one type of creativity, with only a limited number of studies incorporating measures for both facets (Dygert & Jarosz, 2020). Hence, to determine the relative contribution of each mechanism to both types of creativity measures, it is necessary to comprehensively examine the different types of creativity as well as the mechanisms involved (i.e., associative and executive processes).

The main aim of the present study was to investigate whether age-related changes in creativity are mediated by the development of both associative and executive processes. The creative potential in its two facets seems to change during childhood and adolescence (Barbot et al., 2016). Regarding divergent creativity, several studies indicated improvements during childhood and adolescence (e.g., Besançon & Lubart, 2008; Bijvoet-van den Berg & Hoicka, 2014; Charles & Runco, 2001). A recent review by Sadi-Metwaly et al. (2021) concluded that the evidence from studies focused on these ages generally supports an upward trend with some discontinuities. Some other works observed increases in creativity well into early adulthood (e.g., Kleibeuker et al., 2013). However, others have failed to find any differences between adolescents and young adults (e.g., Wu et al., 2005, Lin & Shih, 2022) or have even reported a decreasing trend during late childhood (Lin & Shih, 2016). To complicate matters further, there appears to be differences in the development of different aspects of verbal divergent creativity. For example, originality improved until adulthood (e.g., Kleibeuker et al., 2013; Smith & Carlsson, 1990; but see Lau & Cheung, 2010), whereas fluency and flexibility might reach an asymptotic level of performance before adolescence (e.g., Kleibeuker et al., 2013; Wu et al., 2005).

The development of convergent creativity during childhood and adolescence has been scarcely studied, however, available data suggest improvements over time. Kleibeuker et al. (2013) examined both divergent and convergent creativity across a wide age range (from 12 to 30 years) and reported progressive improvements in convergent creativity during adolescence (from 12-13 years) that continued until early adulthood (18-19 years). In the same vein, Lin and Shih (2016, 2022) also found ascending trends in convergent creativity both during late childhood (8-11 years, in their first study); and during adolescence (12-19 years, in their second study). These authors also observed different age-related patterns in both types of creativity. It has been proposed that the different developmental trajectories for divergent and convergent creativity could be related to the development of the cognitive processes underlying both types of creative functioning (i.e., Gever, et al., 2023; Kleibeuker et al., 2013; Volle, 2018).

One of the motivations of creativity research is to understand the development of creative potential. Examining the cognitive processes underlying creative thinking, especially during school years, may help us to understand the relation between age and creativity. Assuming that associative and executive processes contribute to a different extent to convergent and divergent thinking, they may also lead to different developmental trajectories in both types of creativity. During childhood and adolescence, the executive and associative mechanisms may mature at different rates (Diamond, 2013; Hartung et al., 2020; Huizinga et al., 2006; Luciana et al., 2005). The relative importance of executive and associative processes for performance on each type of creative task, and the course of development of each process may determine age-related differences in creativity measures.

Creativity and Executive Functions

Executive functions (EFs) are a set of general-purpose control processes that regulate one's thoughts and behaviors (e.g., Friedman & Miyake, 2017). The influential factorial model by Miyake et al. (2000) postulates the existence of three independent functions: inhibition, shifting, and updating. Inhibition involves the suppression of dominant information and/or action tendencies that are not relevant to the appropriate goal behaviour, thereby enabling the control of non-relevant responses. Shifting entails changing the focus of attention between strategies and/or responses during task performance. Updating refers to the continuous monitoring, manipulation and substitution of the information held in working memory based on the task requirements. Variation in executive functioning is related to individual differences in performance on complex cognitive tasks (Diamond, 2013), such as reading comprehension (see Butterfuss & Kendeou, 2018, for a review), and mathematical proficiency (see Cragg, & Gilmore, 2014, for a review).

Studies that have examined the relation between these executive functions considered separately and creativity measures yielded inconsistent results. Several studies have documented a relationship between inhibition and divergent creativity (e.g., Benedek, Frank et al., 2012; Edl et al., 2014; Zabelina, & Robinson, 2010;

Zabelina et al., 2012), while others have failed to find an association (e.g., Dorfman et al., 2008). The results for shifting are not consistent either, with some authors reporting a relationship with divergent creativity (e.g., Nusbaum & Silvia, 2011; Pan & Yu, 2016), while others found no such association (e.g., Benedek et al., 2014). Regarding updating, there is some evidence for a relationship both with convergent creativity (e.g., Byrne & Murray, 2005) and with measures of fluency and flexibility in divergent creativity (Benedek et al., 2014; Weis & Wilhelm, 2022). However, in other studies, a working memory (WM) capacity measure predicted convergent creativity, but not divergent creativity scores (e.g., Lee & Therriault, 2013). This diversity of results may be due to the variety of tasks used for evaluating the different executive functions, as well as the creativity measures, which prevents any meaningful comparisons of the results.

There are several studies that have simultaneously examined the three executive functions proposed in the Miyake et al. (2000) model, thereby facilitating comparisons between them (e.g., Benedek et al., 2014; Krumm et al., 2018; Zabelina et al., 2019; Zhao et al., 2021). The results consistently showed that updating was the executive function most strongly related to individual differences in divergent creativity measures (Benedek et al., 2014, with originality; Zabelina et al., 2019, with fluency; Zhao et al., 2021, with fluency and originality). Zhao et al. (2021) also investigated convergent creativity and found that the only related function was updating.

Inhibition, on the other hand, lead to less consistent results. Benedek et al. (2014) reported that inhibition predicted individual differences in originality, whereas Zabelina et al. (2019) did not observe this relationship with the divergent creativity measures, even though inhibition predicted a greater number of creative achievements in the real world. Also, Zhao et al., (2021) failed to find a relation between inhibition and any of the creative measures included.

Finally, the executive function of shifting was generally not related to individual variability in creativity in most of these studies (e.g., Benedek et al., 2014; Zabelina et al., 2019; Zhao et al., 2021), although Krumm et al. (2018) showed that, after controlling for intelligence differences, both shifting and inhibition predicted divergent creativity in children, while WM did not. In their recent review, Palmiero et al. (2022) concluded that both inhibition and WM are critical for divergent creativity whereas the role of shifting (flexibility) remains unclear. The diversity of executive and creativity tasks used, the different scoring methods and analyses carried out, and the lack of a theoretical framework may account for some of the contradictory findings (see Palmiero et al., 2022).

Additionally, some of the previous inconsistent results might be also attributed to the age of participants in each study. For example, participants were children (8-13 year-olds) in Krumm et al.'s study (2018), adolescents (13-15) in Zhao et al.'s study (2021) and adults in Benedek et al.'s (2014) and Zabelina et al.'s (2019) studies. Executive functions undergo changes throughout childhood and adolescence and some of them do not reach maturity until the end of adolescence or even in early adulthood (e.g., Anderson, 2002; Friedman & Miyake, 2017; Hartung, et al., 2020; Jurado & Rosselli, 2007). Thus, to the extent that executive functions determine the performance in creativity tasks, their improvement with age could explain developmental differences in creativity. Therefore, to obtain a deeper understanding of the involvement of executive functioning in age changes in creativity, it is necessary to assess creativity and executive functions at different ages using the same set of problems and tasks.

Creativity and Associative Processes

In addition to executive functions, creativity has also been related to associative processes. The ability to strategically search and retrieve information from memory quickly and efficiently plays a central role in producing creative ideas (e.g., Beaty et al., 2014; Dygert & Jarosz, 2020; Lee & Therriault, 2013). Traditionally, the effectiveness of memory retrieval has been assessed by means of verbal fluency tasks. Several previous studies examined creativity performance in conjunction with verbal fluency, as a measure of associative processing, and measures of intelligence (Benedek, Könen et al., 2012; Silvia et al., 2013) and WM capacity (Dygert & Jarosz, 2020; Lee & Therriault, 2013).

The fluency and flexibility aspects of divergent tasks may be related to verbal fluency (e.g., DeYoung et al., 2008; Lee & Therriault, 2013), although such a relationship does not necessarily imply identical cognitive processes. In verbal fluency tasks, the goal is to strategically search one's memory to retrieve as many relevant items as possible, based on a specific cue. In divergent creative tasks, the individual has to simultaneously explore various options and search for distant and unusual associations between different concepts. Verbal fluency was found to predict performance in both divergent and convergent thinking tasks, although sometimes a stronger relationship was observed with divergent measures (e.g., Dygert & Jarosz, 2020), and other times, with convergent measures (e.g., DeYoung et al., 2008; Lee & Therriault, 2013).

Verbal fluency (both semantic and phonological) grows during childhood and adolescence (e.g., Arán Filippetti & Allegri, 2011; Klenberg et al., 2001; Korkman et al., 2001; Matute et al., 2004; Sauzéon et al., 2004). It has been argued that age-related improvements in phonological fluency reflect the development of a strategic component of linguistic change, while changes with age in semantic fluency are associated with the enrichment of semantic knowledge and a more effective access to it (Sauzéon et al., 2004). These improvements in semantic and phonological fluency might mediate the age-related changes in creativity.

The Present Study

The present study aimed to examine age-related changes in convergent and divergent creativity during the primary, secondary school and university educational levels. Based on the literature reviewed earlier, we expected to find an age-related improvement in creativity measures. As reported by Kleibeuker et al. (2013) and Lin and Shih (2016; 2022), it might be possible to observe differences in the patterns of age-related changes in divergent and convergent creativity.

Cognitive functions that undergo changes with age, such as executive and associative processes, may explain age differences in both types of creativity. Other authors also highlight the importance of controlled and spontaneous processes, and how the trade-offs between the two forms of processing may explain age-related differences in creativity. For example, Preiss (2022) proposed that controlled cognition becomes more influential as creativity develops. Thus, the second objective of this study was to determine to what extent possible age-related changes in both types of creativity are mediated by changes in executive functioning and associative processing. Given that some executive functions, such as inhibition, mature early; whereas others, such as updating in working memory, control flexibility, or interference control, continue to develop well until adolescence and adulthood (e.g., Diamond, 2013; Hartung et al., 2020; Huizinga et al., 2006; Luciana et al., 2005), it was expected that age changes in creativity would be related to a greater extent with differences in updating and to a lesser extent with differences in inhibition. Furthermore, the different executive functions could play a different role in mediating the relationship between age and the different measures of creativity (see Zhao et al., 2021). For example, shifting could be more important for fluency or flexibility measures than for the originality measure (Pan & Yu, 2016), and the same could occur in relation to inhibition (Benedek, Franz et al., 2012).

Finally, we examined the possible mediational role of verbal fluency in explaining the relationship between age and divergent and convergent creativity. Individual differences in associative processing have been associated with variation in creative thinking (Benedek, Könen et al, 2012; Dygert & Jarosz, 2020; Lee & Therriault, 2013). It is well established in the literature that verbal fluency, as a measure of associative abilities, has a good predictive validity for creative thinking, which appears to be more pronounced for convergent than divergent thinking (i.e., DeYoung et al., 2008; Lee & Therriault, 2013). Given that verbal fluency changes markedly during childhood and adolescence (e.g., Klenberg et al., 2001; Korkman et al., 2001; Matute et al., 2004; Sauzeon et al., 2004), fluency could also contribute to explain possible age-related differences in creativity.

Method

Participants

The participants in the study were mainly White children attending two primary and two secondary schools, and students from the University of Jaén. All participants were native Spanish speakers. The schools were located in a medium-sized city in the south of Spain, and the school community was predominantly composed of families with a medium socio-economic status. Four hundred and twenty-seven students (249 female) from different educational levels were recruited as participants. One hundred and forty-six (74 girls) were fifth- and sixth-grade children from primary school (mean age = 11.56 years, *SD* = 0.74; age range = 9.39-13.37); one hundred and thirty-one (70 girls) were ninth and tenth-grade children from secondary school (mean age = 15.58 years, *SD* = 0.86; age range = 14.30-17.22); and one hundred and fifty (114 female) were university students enrolled in a psychology degree (mean age = 20.18 years, *SD* = 3.42; age range = 17.91-42.50). None of the participants had specific learning difficulties. The school's team approved the activities carried out in the study, and the University's Research Ethics Committee approved the study. Informed consent was obtained from the older participants (i.e., undergraduate students) and from the parents of the children and adolescents. Additionally, verbal assent was given by children and adolescents.

Materials

Creativity Tasks

Three different tasks were used to assess creativity, one for divergent creativity (Alternative Uses Task) and two for convergent creativity (insight problems and Remote Associate Task). The Alternative Uses Task (AUT, Guilford, 1967) problems required participants to indicate as many unusual and original uses for a brick and a newspaper. Two minutes were given for each item. The three classical dimensions of divergent thinking were scored: number of different uses (fluency); number of different categories for these uses (flexibility); and degree of uniqueness (originality). Incomplete, non-understandable ideas and repetitions were excluded prior to scoring. No other exclusion criteria were applied. Two independent coders assigned each response given to a category. The interrater agreement was 97%. When agreement was not reached, an additional coder (last author) intervened to resolve the discrepancies through discussion. The fluency score was calculated by summing the total number of different responses. The flexibility score was computed as the number of different categories produced (i.e., one point per each different use). An originality score for each category was derived from the infrequency transformation (1- relative frequency; see Reiter-Palmon et al., 2019), with relative frequency calculated as the occurrence of a category across the total of solutions for this category. The final originality score was the average of the originality scores across all the different uses (categories) given by each participant. In the present sample, internal consistencies (Cronbach's α) were .82, .77 and .52 for fluency, flexibility and originality measures respectively.

The insight problems required to solve six problems obtained from various internet sites devoted to lateral thinking (e.g., a child playing on the beach has six piles of sand in one place and three piles in another. If he puts all the piles together, how many piles of sand would he have? Answer: one pile). These problems were similar to those used by other authors (e.g., DeYoung et al., 2008; Lin & Shih, 2016). Participants had two minutes to solve each one. A point was awarded for each correct solution. The number of problems correctly solved was taken as the final score. This measure showed very poor internal consistency (Cronbach's $\alpha = .42$) and consequently was excluded from subsequent analyses.

Remote Association Task (RAT; based on Mednick, 1962). Forty problems were selected according to their difficulty from the set of remote associate problems validated for use with Spanish-speaking populations (Peláez-Alfonso et al., 2020). Two lists of 20 items each were presented. The first list was composed of twenty triads of words (e.g., cheese, computer, and elephant) that had a semantic relationship with a fourth solution word (e.g., mouse), which the participants had to find out. The second list was also composed of twenty word-expression and compound word problems (e.g., "volley, basket, foot", and the word solution "ball"). Before presenting each word-triad list, three practice examples were provided for each type of relationship. The time available for each list of 20 problems was 8 minutes. Each correct answer was awarded a score of 1, for a total possible score of 40 points. The number of correctly solved problems was taken as the final score. The internal consistency in the present sample was α = .81.

Executive Function Tasks

Inhibition Tasks. Two inhibition tasks were used. A numerical Stroop task (adapted from Lee et al., 2009) was used to measure the ability to inhibit competing stimuli (interference control). In each trial, a string of 1 to 4 digits (e.g., 111) or asterisks (e.g., ***) appeared on the screen. The task included three conditions. Non-numeric stimuli (e.g., three asterisks: ***) and digit strings (e.g., 222) were presented in the first condition and in the other two conditions, respectively. In the congruent trials, the number of digits corresponded to the numerical value of each individual digit (e.g., 4444). For incongruent trials, the number of digits did not correspond to the numerical value of the individual digit (e.g., 222). The digit strings varied from 1 to 4, so that their numerosity could be determined directly. Participants had to indicate the number of symbols (digits or asterisks) displayed on the screen by pressing the corresponding key on the keyboard. Twelve practice trials were administered, followed by four blocks of 24 experimental trials. In each experimental block, an equal number of trials from each of the three conditions were presented in random order. The dependent measure was obtained by subtracting the mean response time (RT) for the congruent condition from the mean RT of the incongruent condition (Cronbach's α = .58).

The go/no-go task (adapted from Logan & Cowan, 1984) was used to assess response inhibition, that is, the ability to inhibit a dominant response. Single capital letters (from A to Z) were displayed at the center of the screen to which the participant had to respond by pressing the space key as quickly as possible, with the exception of the letter "X", in which case no key had to be pressed. Each trial started with a 200 ms fixation point, followed by a 500 ms target letter. The participant had to respond during an interval of 2000 ms after the letter appeared by pressing a key labelled "YES". After the answer was given (or after the allotted time of 2000 ms had elapsed), a black or red fixation point (*) was displayed for 200 ms for correct and incorrect answers, respectively. The test consisted of two lists of 128 trials, separated by a short pause. The number of hits and false alarms was recorded. The dependent variable was the sensitivity parameter *d’,* calculated by subtracting the *z*-score for the false alarms from the *z*-score for the hits. The fourth method proposed by Stanislaw and Todorov (1999) was used to avoid indeterminate *d’* values in the case that the proportion of false alarms or hits was 0 or 1, respectively (Cronbach’s α = .88).

Switching Tasks. Two tasks, the number-letter task and the plus-minus task (adapted from Lee et al., 2009 from the tasks used by Miyake et. al, 2000), were employed to assess task switching. In the number-letter task, a number-letter pair (e.g., A2, N1) was presented in one of the four corners on the screen. The specific task to be performed was cued by the position on the screen (top or bottom) where the items appeared. When the number-letter pair was presented at the top of the screen, participants had to indicate whether the number was odd or even. When the item appeared at the bottom of the screen, they had to decide whether the item included a consonant or a vowel. Participants had to respond by pressing the key labelled “yes” for vocals and odd numbers and pressing the key labelled “no” for consonants and even numbers. Three blocks of trials were included; the first two were single-task blocks that contained 36 trials each and did not require switching between tasks because they involved either an odd/even or a vowel/consonant judgement. In the third mixed-task block (144 trials, into four sub-blocks of 36 trials), items were presented in a clockwise direction, so that participants had to switch between the two tasks on alternate trials.

Several practice trials were presented in each block: 10 for the single-task and 20 for the mixed-task block. Switching costs were calculated by subtracting the average RT of the switch from the average RT of the non-switch trials (Cronbach's α = .87).

In the plus-minus task, a series of two-digit numbers (printed in red or blue) were presented on the computer screen. When red numbers were shown, participants had to add 2 to that number and type the result using the keyboard. When blue digits were presented, participants had to subtract 2. There were four blocks of experimental trials. In the first single-task block, all the numbers were red (i.e., additions). In the second single-task block, all the numbers were blue (i.e., subtractions). In the third and fourth mixed-task blocks, a mix of red and blue numbers was presented in pseudo-random order. There were also an initial 12 practice trials block. Participants were instructed to complete the task quickly and accurately. Switching costs were calculated as in the Number-Letter task (Cronbach's α = .51).

Updating Tasks. Two updating tasks were used, the numerical n-back task and the arithmetic updating task. In the *n*-back task (Kirchner, 1958; adapted from Linares et al., 2019), a series of digits (from 1 to 9) were presented sequentially in the centre of the computer screen, some of which were repeated in the list. Each item was presented for 2500 ms with a pause of 500 ms between them. Participants had to determine, by pressing the "yes" or "no" labelled key, whether the item presented matched the one presented *n* trials back in the sequence. There were three *n*-back levels (1-back, 2-back and 3-back). Each list contained 31, 32, or 33 items depending on its level (1, 2, or 3-back), of which 10 were targets requiring "yes" responses and the rest were non-targets involving "no" responses. For each *n*-back level, a practice list and two experimental lists were administered. The number of correct answers and false alarms was recorded. The dependent variable was the sensitivity parameter *d′* calculated as in the go/no-go task, subtracting the *z*-score for the false alarms from the *z*-score for the hits (Cronbach's α = .79).

The arithmetic updating task (Oberauer et al., 2003; adapted from Linares et al., 2019) required memorizing numbers that appeared inside boxes, performing arithmetic operations with those numbers, and updating the value associated with the boxes. The number of boxes varied according to the memory load (1, 2, or 3). After the initial numbers (from 1 to 3, depending on the memory load) were presented, an arithmetic operation (simple additions or subtractions between 1 and 3) appeared in one of the three possible squares. Both, the initial items and the operations, were presented for 2500 ms with a 500 ms pause between items. Participants had to memorize the initial numbers, perform the arithmetic operations with those numbers, and remember the final results obtained. At the end of the list, they had to type the last number memorized for each box. The task included 4 blocks of trials. The first was a practice block, in which three lists of 9 or 10 items each were presented. The first list implied a memory load of one item, while the next two practice lists required keeping two items in memory. Once the practice was finished, the next three blocks of experimental trials, each one composed of three trial lists including 11 to 13 items, were presented. Memory load increased from one in the first block to three in the third block. The dependent variable was the number of correct answers (Cronbach's α = .68)

Verbal Fluency Tasks

Following Lee and Therriault's study (2013), participants completed two verbal fluency tasks. In the letter fluency task, participants were asked to generate as many words that begin with the letter P (2 min) and M (2 min) as possible. The total score was the number of appropriately named words (Cronbach's α = .85). The category fluency task, required participants to generate a list of as many different types of animals (2 min) and jobs (2 min) as possible. The total score was the number of appropriately named animals and jobs given (Cronbach's α = .81).

Procedure

The tasks were administered in two separate sessions which lasted between 90 and 120 minutes. Subjects were given rest periods in each session. In the first session, the participants were assessed in group settings in their classrooms. They were given a booklet that contained the tasks in the following fixed order: letter fluency, category fluency, alternative uses task, insight problems and RAT problems.

In the second session, computerized executive functions tasks were completed in groups of 12 to 15 students. The order of the tasks was the same for all the participants: Go/no-go, *n*-back, number-letter, plus-minus, numerical Stroop, and arithmetic updating tasks. The E-prime 2.0 software (Schneider et al., 2002) was used for programming and presenting the different tasks and recording the responses. The tasks were administered using laptop computers with a 15-inch screen.

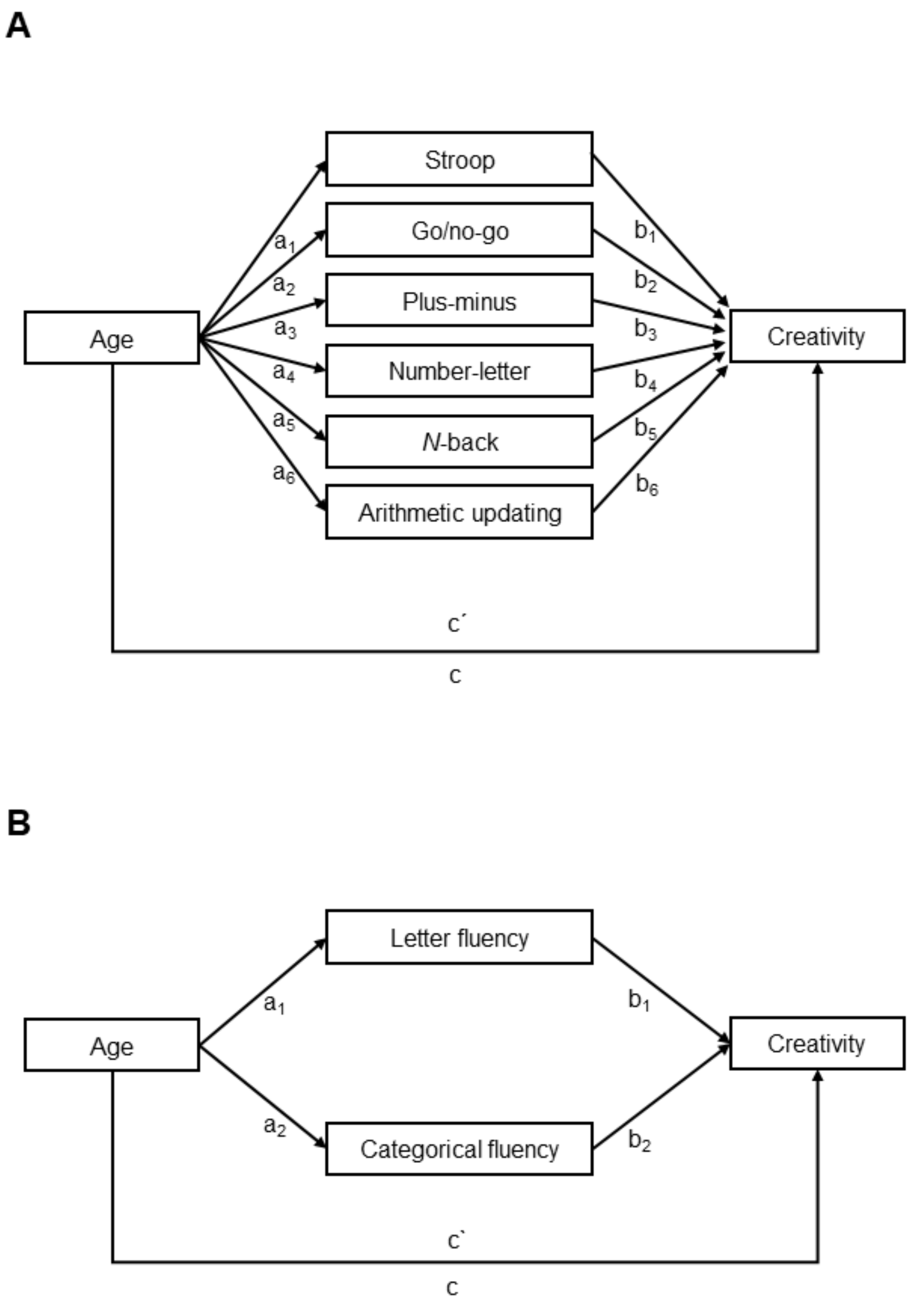
Data Analyses

Altogether, 427 subjects completed the first session assessment; however, some of them were excluded from some analyses due to missing data, lack of compliance with a task or other issues. Specifically, 27 participants did not attend the second session. Some participants might have had difficulties to understand the instructions of a particular task and failed to perform it properly (Stroop task: 4, go/no-go task: 2, plus-minus task: 7, number-letter task: 2, *n*-back task: 4, arithmetic updating task: 3). Data from some participants were lost due to procedural errors (Stroop task: 1, go/no-go task: 13, plus-minus task: 2, arithmetic updating task: 3). Finally, two participants did not complete the verbal fluency task.

The analysis consisted of several steps. Initially, univariate analyses were performed to test for age-group differences on each of the performance measures. Then, two sets of multiple mediation analyses were conducted to examine the possible mediating role of executive functions and verbal fluency on the relationship between age and creativity. The variables included as mediators were standardized to ensure they were in the same scale and thus, facilitate their comparison. The two general models for executive functions and verbal fluency mediators are shown in Figure 1, panels a and b, respectively. The coefficient *a* estimated the effect of age on the mediator variables (executive functions or verbal fluency). The coefficient *b* estimated the effect of the mediator variables on creativity measures. The specific indirect effect of age on creativity measures through mediator variables was the product *a* x *b.* The total effect *c* was the relationship between age and creativity measures without taking into account any indirect effect. The direct effect *c'* quantified the effect of age on creativity measures that was independent of the indirect effects. Therefore, *c*' was equivalent to subtracting the total indirect effect from the total effect of age on creativity measures (*c*). Analyses were conducted using the lavaan R package (Rosseel, 2012). A Monte Carlo power analysis for complex mediation (R bmem version 2.0; Zhang, 2014) suggested that a sample of 400 participants was sufficient to detect an indirect effect when standardized beta values for the *a*, *b* and *c*' paths were larger than 0.2 (i.e., small/medium effect), with an alpha level of 0.05 and a power ($1 - \beta$) of 0.80.

Figure 1

General Models for Executive Functions (Panel A) and Verbal Fluency (Panel B) as Mediators on the Relationship between Age and Creativity.



In order to disentangle the contribution of associative and executive processes to both types of creativity, we estimated the unique and shared variance in creativity measures accounted for by executive functions, verbal fluency and age. To this end, we followed the variance-partitioning procedure described by Chuah and Maybery (1999;

see also Salthouse, 1994) that have subsequently been used to decompose the variance of cognitive measures (e.g., Conway et al., 2021; Giofrè et al., 2014; Unsworth & Spiller, 2010). For each criterion variable (i.e., the different aspects of creativity), a series of regression analyses were performed by entering different combinations of the predictor variables: age, executive functions and fluency. Thus, for instance, the unique contribution of a given predictor variable (e.g., age) to the prediction of the different aspects of creativity could be determined by subtracting the R^2 value of the regression model that included the two other predictors (executive functions and verbal fluency) from the R^2 value of the regression model that included all the three predictors. The same logic can be implemented to estimate the shared contribution of any combination of predictors. Because in this study there were several indicators for each predictor (i.e., various measures of executive functions), the different indicators of the same predictor were entered as a single block in the regression models. All statistical analyses were conducted using R (version 4.0.2; R Core Team, 2020).

Results

Preliminary analyses

Table 1 presents descriptive statistics for all measures used in subsequent analyses, and the results of the univariate analyses to determine possible differences between educational-level groups. Secondary-school students showed superior performance in all the executive function tasks compared to primary-school students, except in the plus-minus task, in which differences were found only between primary-school and university students. However, with some exceptions, no significant differences were found between the secondary-school and university groups in most of the tasks. Only gradual improvements up to the university level were observed in the *n*-back updating task and in the letter fluency performance. Of particular interest to this study were the results indicating significant performance gains in all divergent and convergent measures from primary to secondary school levels. Additionally, gradual improvements in originality (AUT score) and in remote associates problem solving (RAT score) were found from the secondary to the university level.

Table 2 reports zero-order correlations (below the diagonal) and partial correlations controlling for educational level (above the diagonal) among all the outcome measures included in this study. Regarding executive functions, there was a consistent relationship between inhibition (specifically for the go/no-go task) and updating measures (higher for the *n*-back task) and several measures of divergent (flexibility and originality) and convergent creativity. The switching cost showed no relationship with the creativity measures, except between one task (number letter) and the RAT. Notably, the highest correlations were found between verbal fluency and the measures of both divergent and convergent creativity. After controlling for educational level, the correlations decreased in magnitude, even becoming non-significant, indicating that age explained part of the relation among the different variables. In the plus-minus task, an inverse pattern was observed, with a small positive relationship between the switching cost and measures of flexibility and creative originality when controlling for educational level.

Table 1

Mean and Standard Deviations of the Outcome Measures and Results of ANOVAs on Outcome Measures for Educational Level.

	Primary (P)		Secondary (S)		University (U)		ANOVA		
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	df	*F*	Post-hoc analyses
Executive Functions									
Stroop	84.67	108.63	42.44	67.76	28.00	60.66	2. 392	17.19 **	P<S & U; S=U
Go/no-go	1.97	0.85	2.90	0.72	3.06	0.85	2. 382	68.53 **	P<S & U; S=U
Plus-minus	399.90	430.55	335.35	254.69	254.61	232.37	2. 388	6.86 **	P=S; P<U; S=U
Number-letter	453.25	302.95	323.14	160.25	292.41	134.49	2. 395	21.55 **	P<S & U; S=U
N-back	2.08	0.58	2.60	0.58	2.79	0.51	2. 393	57.47 **	P<S<U
Arith. updating	44.94	17.00	55.70	16.84	56.82	18.30	2. 391	18.76 **	P<S & U; S=U
Verbal Fluency									
Letter fluency	11.43	3.63	17.18	4.14	19.60	4.49	2. 424	153.83 **	P<S<U
Category fluency	15.39	4.10	22.35	3.95	22.86	4.24	2. 424	149.62 **	P<S&U; S=U
Creativity									
Fluency (AUT)	6.69	2.99	7.90	2.93	7.22	2.67	2. 422	6.11 *	P<S; P=U; S=U
Flexibility (AUT)	4.56	2.08	5.81	2.00	5.93	1.99	2. 422	20.16 **	P<S & U; S=U
Originality (AUT)	0.65	0.14	0.70	0.09	0.73	0.08	2. 422	17.82 **	P<S<U
RAT	16.97	4.65	24.07	5.18	25.70	4.77	2. 424	133.07 **	P<S<U

Note. ** p<.001; * p<.05

AUT: Alternative Uses Task; RAT: Remote Associate Test

Table 2

Pearson Correlation Coefficients for the Outcome Measures. Zero-Order Correlations, below the Diagonal; and Partial Correlations after Controlling for Educational Level, above the Diagonal.

	1	2	3	4	5	6	7	8	9	10	11	12
1. Stroop	1	-.14*	.02	.02	-.17*	-.16*	-.16*	-.17*	-.02	-.06	-.05	-.13*
2. Go/no-go	-.24**	1	.02	.04	.44**	.33**	.21**	.23**	.01	.07	.06	.32**
3. Plus-minus	.07	-.07	1	.13*	.02	.08	-.03	.04	.14*	.11*	.07	.06
4. Number-letter	.09	-.09	.18*	1	-.06	-.08	-.07	-.13*	-.03	-.03	-.02	-.09
5. N-back	-.26**	.54**	-.06	-.16*	1	.35**	.27**	.31**	.04	.13*	.11*	.33**
6. Arith. updating	-.21*	.40**	.03	-.14	.41**	1	.20**	.29**	.02	.06	.08	.33**
7. Letter fluency	-.27**	.42**	-.13	-.22*	.43**	.30**	1	.62**	.33**	.39**	.28**	.44**
8. Category fluency	-.27**	.41**	-.06	-.25**	.45**	.37**	.73**	1	.40**	.45**	.33**	.50**
9. Fluency (AUT)	-.05	.05	.12	-.06	.08	.04	.32**	.39**	1	.85**	.47**	.08
10. Flexibility AUT)	-.13	.18*	.05	-.10	.22**	.12	.46**	.51**	.84**	1	.61**	.17*
11. Originality (AUT)	-.11	.17*	.02	-.09	.20*	.13	.37**	.40**	.47**	.64**	1	.11*
12. RAT	-.24**	.47**	-.04	-.21**	.46**	.40**	.59**	.62**	.11	.27**	.21**	1

Note. ** p<.001; * p<.05

AUT: Alternative Uses Task; RAT: Remote Associate Test

Mediation of executive functions on creativity

A set of multiple mediation analyses was conducted to determine whether aged-related differences in creativity were mediated by executive functions (see Figure 1, panel a, for the general model). The results of the mediation models are presented in Table 3 and in Supplementary Figure 1.

Age was found to be a significant predictor of all executive function measures (paths *a*). Most of the executive functions did not significantly predict divergent creativity measures (paths *b*), except the plus-minus task on fluency, and *n*-back task on flexibility and originality measures. This result lowers the probability that executive functions mediate the relationship between age and divergent creativity. In fact, none of the indirect effects of executive measures (*a* x *b*) were significant, except for the indirect effects of updating (*n*-back) on flexibility and switching (plus-minus) on fluency. The total effect of age was significant for the flexibility and originality measures, and remained significant when the indirect effect of updating was considered (path *c*'). Thus, updating explained only part of the effect of age on one measure of divergent creativity.

As for the convergent creativity measure, both updating tasks predicted creativity measure. Besides, the go/no-go inhibitory measure also predicted the RAT scores. These executive function measures were, in addition, significant mediators of the relation between age and convergent creativity. The switching cost in the number-letter task also predicted the RAT scores, but the indirect effect of age through switching (*a* x *b*) was not significant. Thus, the total effect of age was partially mediated by updating and inhibition.

Table 3

Standardized Direct and Indirect Effects of Executive Functions on Creativity Measures

Outcome	Mediator		*a*	*b*	*a x b*	95% CI	*c'*	*c*
Fluency (AUT)							.10	.09
	Inhibition	Stroop	-.27**	.01	.00	[-.02, .02]		
		Go/no-go	.44**	-.04	-.02	[-.05, .02]		
	Switching	Plus-minus	-.18**	.13*	-.02*	[-.03, .00]		
		Number-letter	-.30**	-.04	.01	[-.01, .03]		
	Updating	N-back	.39**	.05	.02	[-.02, .04]		
		Arith. updating	.23**	.01	.00	[-.01, .02]		
Flexibility (AUT)							.23**	.28**
	Inhibition	Stroop	-.27**	-.02	.00	[-.01, .02]		
		Go/no-go	.44**	-.02	-.01	[-.03, .02]		
	Switching	Plus-minus	-.18**	.10	-.02	[-.02, .00]		
		Number-letter	-.30**	-.03	.01	[-.01, .02]		
	Updating	N-back	.39**	.12*	.05*	[.00, .04]		
		Arith. updating	.23**	.03	.01	[-.01, .01]		
Originality (AUT)							.22**	.26**
	Inhibition	Stroop	-.27**	.00	.00	[.00, .00]		
		Go/no-go	.44**	-.02	-.01	[.00, .00]		
	Switching	Plus-minus	-.18**	.08	-.01	[.00, .00]		
		Number-letter	-.30**	-.03	.01	[.00, .00]		
	Updating	N-back	.39**	.11*	.04	[.00, .00]		
		Arith. updating	.23**	.06	.01	[.00, .00]		
RAT							.26**	.48**
	Inhibition	Stroop	-.27**	-.06	.02	[-.01, .05]		
		Go/no-go	.44**	18**	.08**	[.04, .17]		
	Switching	Plus-minus	-.18**	.05	-.01	[-.03, .01]		
		Number-letter	-.30**	-.09*	.03	[.00, .07]		
	Updating	N-back	.39**	17**	.07**	[.04, .14]		
		Arith. updating	.23**	.18**	.04**	[.02, .09]		

Note: ** $p < .001$, * $p < .05$; *a*: effects of age on executive functions; *b*: effects of executive functions on creativity measures. *a x b*: indirect effects of age on creativity through executive functions; *c'*: direct effects of age on creativity measures; *c*: total effects of age.

AUT: Alternative Uses Task; RAT: Remote Associate Test;

Mediation of verbal fluency on creativity

Another set of multiple mediation analyses was conducted to assess whether aged-related differences in creativity were mediated by verbal fluency (see Figure 1, panel b). The results of these models are presented in Table 4 and in Supplementary Figure 2.

Table 4

Standardized Direct and Indirect Effects of Verbal Fluency on Creativity Measures

	Mediator	*A*	*b*	*a x b*	95% CI	*c'*	*c*
Fluency (AUT)						-.19**	.09*
	Letter fluency	.57**	.17**	.10**	[.02, .11]		
	Categorical fluency	.51**	.37**	.19**	[.09, .17]		
Flexibility (AUT)						-.05	.28**
	Letter fluency	.57**	.23**	.13**	[.03, .09]		
	Categorical fluency	.51**	.38**	.19**	[.07, .12]		
Originality (AUT)						.03	.26**
	Letter fluency	.57**	.15*	.08*	[.00, .00]		
	Categorical fluency	.51**	.29**	.15**	[.00, .01]		
RAT						.17**	.50**
	Letter fluency	.57**	.23**	.13**	[.11, .26]		
	Categorical fluency	.51**	.39**	.20**	[.21, .36]		

Note: ** $p < .001$, * $p < .05$; *a*: effect of age on verbal fluency measures; *b*: effect of verbal fluency measures on creativity measures; *a x b*: indirect effects of age on creativity through fluency; *c'*: direct effect of age on creativity measures; *c*: total effect of age.
AUT: Alternative Uses Task; RAT: Remote Associate Test

Age was found to be a significant predictor of both verbal fluency scores (paths *a*). Both measures of verbal fluency significantly predicted all the divergent and convergent creativity measures (paths *b*). The indirect effects (*a* x *b*) of the two mediators were significant in all the creative measures. The direct effect of age on flexibility and originality, which was initially found to be significant (path *c*), became non-significant when the mediator variables were considered (path *c′*). Thus, the effect of age on these measures was fully mediated by verbal fluency. There was an inconsistent mediation effect on creative fluency since the direct effect of age had an opposite sign to the mediating effects of both measures of verbal fluency.

Regarding convergent creativity, the total effect of age was significant, however, the direct effect of age (*c′*) remained significant, indicating partial mediation of both verbal fluency variables in the age-difference on RAT performance.

Variance-partitioning analysis

The unique and shared contributions of age, verbal fluency and executive functioning to predicting the various creativity measures were estimated using the variance partitioning procedure described by Chuah and Maybery (1999). The Venn diagrams of the unique and shared portions of variance between the three predictors are represented in Figure 2. The results for each criterion variable are presented in Table 5.

Regarding divergent creativity, the overall contribution of the three predictors to flexibility, fluency and originality measures was 28.28%, 21.46% and 18.09%, respectively. Verbal fluency explained the largest portion of the unique variance in all the three divergent creativity measures, representing more than half of the total variance explained for each criterion, and reaching almost 80% in the case of creative fluency. The unique contributions of age and executive functions to predicting divergent creativity measures were very small. In fact, age and the measures of executive function only made a modest shared contribution with verbal fluency in explaining the different measures of divergent creativity.

Figure 2

Venn Diagram of the Unique and Shared Portions of Variance in a Given Creativity Measure Accounted for by Age, Executive Functions and Verbal Fluency

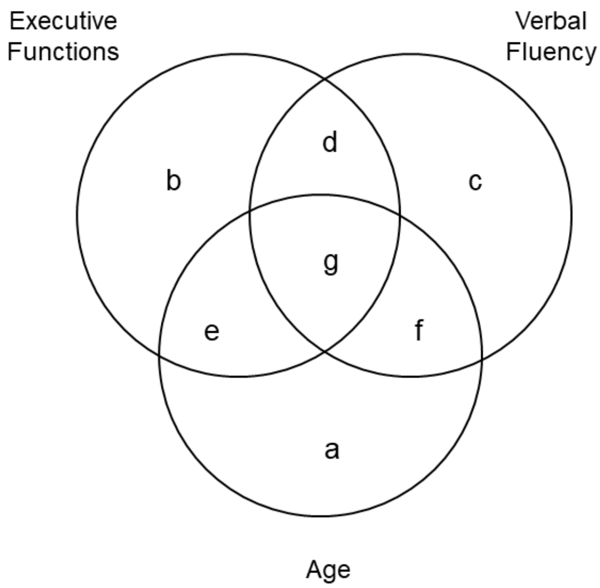


Table 5

Unique and Shared Variance (R^2) in Creativity Accounted for by: Age, Executive Functions, and Verbal Fluency.

	Comp.	Flexibility (AUT)	Fluency (AUT)	Originality (AUT)	RAT
Unique contribution of Age	A	0.06	0.55	0.40	0.65
Unique contribution of EF	B	0.53	1.84	0.35	2.91
Unique contribution of VF	C	18.23	17.04	8.78	11.37
Shared contribution of EF and VF	D	2.30	0.00*	2.15	9.84
Shared contribution of Age and VF	E	4.25	0.28	3.35	4.93
Shared contribution of Age and EF	F	0.07	1.75	0.00*	1.13
Shared contribution of Age, EF and VF	G	2.83	0.00*	3.05	16.48

Note: * negative values (between -0.3 and -0.2) that were set to 0.

EF: Executive functions; VF: Verbal Fluency. AUT: Alternative Uses Task; RAT: Remote Associate Test

The total variance explained by the three predictors in convergent creativity was 47.31%. As with divergent creativity, verbal fluency made a substantial independent contribution to convergent creativity measure, whereas the unique contributions of executive functions to convergent creativity measures were rather small. Age failed to make a unique contribution, indicating that age-related changes in convergent creativity were entirely mediated by executive functions and verbal fluency.

Discussion

The present study examined possible age-related changes across different measures of convergent and divergent creativity. Our primary goal was to determine the extent to which age-related changes in creativity are mediated by executive functions and verbal fluency. The results revealed clear age-related improvements in all the creativity measures used in the study, mainly between primary and secondary school, although, in some cases, even up to the university level. Importantly, executive functions and verbal fluency accounted for most of the age-related differences in convergent and divergent creativity.

The relative contributions of executive functioning and verbal fluency to creativity

The dual-process view of creativity predicts that both executive and associative processes play a role in high-level creative processes. Therefore, before discussing the possible mediating role of executive and associative processes in the relationship between age and creativity, it is important to examine the correlations between executive functions, verbal fluency, and creativity.

In line with previous studies, the present results indicate that updating, especially when measured with the *n*-back task, is the executive function most strongly associated with both convergent (Zhao et al., 2021) and divergent creativity (e.g., Benedek et al., 2014; Zabelina et al., 2019; Zhao et al., 2021). Regarding inhibition, our results are also consistent with other studies showing a relationship with divergent creativity (i.e., Benedek, et al., 2014, but see Zabelina et al., 2019 and Zhao et al., 2021). It is worth noting that, for the originality and flexibility measures, correlations were observed only with the go/no-go task, which is thought to reflect suppression of dominant or automatic responses; but not with the Stroop task, which taps into inhibition of interfering information (e.g., Nigg, 2000; Rey-Mermet et al., 2018). Our results show a consistent relationship of both inhibitory tasks with convergent creativity. However, in the study by Zhao et al. (2021), inhibition was not related to convergent creativity, although it is possible that the combined measure obtained from different inhibitory tasks used in that study masked some specific relationship between one type of inhibition and creativity. The variety of inhibitory tasks used in previous studies has also been suggested by Palmiero et al. (2022) as a possible explanation for the discrepant results observed in inhibition. Finally, with regard to shifting and creativity measures, except for the relationship between the RAT and the number-letter task, no other significant correlations were observed, which is consistent with previous findings (Benedek et al., 2014; Zhao et al., 2021). In their recent review, Palmiero et al. (2022) suggested that the contribution of shifting to divergent thinking may depend on the person's abilities, as well as on the instructions and difficulty of the task. Broadly, these results align with previous studies that have reported links between creativity and executive functioning, as well as intelligence, which serves as a proxy for executive functioning (see Benedek & Jauk, 2018, for a review).

Our results also underline the role of associative processes in creativity. In fact, the strongest relationships emerged for verbal fluency with measures from both types of creativity, which is in line with previous research (see metanalysis by Gerver et al., 2023). In addition, the involvement of verbal fluency seemed to be greater for divergent than for convergent creativity (see Dygert & Jarosz, 2020, for a similar finding). The role of associative processes in performing the search in long-term memory could be crucial in creative tasks, as increasingly more diverse ideas have to be accessed in order to come up with original ideas.

A partitioning-variance method was used to investigate the relative importance of executive functioning and fluency in explaining differences in creativity. It should be considered that, for example, verbal fluency tasks may reflect not only associative processing but also executive functioning. This method makes it possible to identify the unique and shared variance between the two constructs. We found that most of the variance in divergent creativity was explained uniquely by the fluency measures, whereas most of the variance in convergent creativity was better accounted for by combinations of the different predictors.

The dual-processes view of creative thinking (Beaty et al., 2014; Benedek & Jauk, 2018; Dygert & Jarosz, 2020; Gilhooly & Fioratou, 2009; Lee & Therriault, 2013) propose that both executive and associative processes explain, to different degrees, performance in divergent and convergent thinking. Dygert and Jarosz (2020) reported that fluency had an important role on performance on both divergent and convergent tasks, above and beyond the effect of WM. Working memory, on the other hand, had a direct role in convergent tasks, while its contribution to divergent tasks was indirect, through fluency processes. The results of our study support the dual-process theory in creative thinking, confirming that associative and executive processes predict substantial and unique variance in divergent and convergent creative. Notably, the associative measures showed a more important role in predicting creativity compared to the executive measures. These findings are consistent with the recent meta-analysis by

Gerver et al. (2023), which indicates that the fundamental basis of creative behavior, both convergent and divergent, is the ability to retrieve information from semantic memory. Also, in line with present results, Gerver et al., (2023) showed that working memory (including updating and inhibition) appears to be less relevant to divergent compared to convergent thinking. Finally, our data indicate that there was an amount of shared variance between associative and executive measures that accounted for additional variance in the measures of creativity. These findings highlight the necessity of assessing executive and associative functioning simultaneously to ascertain the unique contribution of each mechanism to creativity.

Age-Related Differences in Creativity

Results showed age-related improvements in the three measures of divergent creativity (fluency, flexibility, and originality) from primary to secondary-school level. No differences were observed between the secondary-school level and the university level in fluency and flexibility. This pattern resembles that reported by Sadi- Metwaly et al. (2021) which observed a slump in creativity around 7h grade. There was a noticeable difference in originality across age groups. Several other studies have also shown protracted maturation of originality compared to fluency and flexibility (Kleibeuker et al., 2013; Smith & Carlsson; 1990; although see Lin & Shih, 2022; for a somewhat different pattern). It has been proposed that fluency and flexibility tap the quantitative aspect of divergent thinking, while originality entails the qualitative side of creative ideation (Guilford, 1967; Runco, 2007). The quantitative and qualitative dimensions of divergent thinking show different patterns of correlations with other cognitive and personality measures, and load on distinct latent factors (i.e., Benedek, Franz et al., 2012). Therefore, a logical conclusion from our results is that divergent creativity in its qualitative dimension, which is considered the key component of divergent thinking (Runco & Jaeger, 2012), improves with age, at least, until young adulthood.

Regarding convergent creativity, we found an age-related increase in the number of RAT problems solved. These results are also consistent with those reported by Kliebeuker et al. (2013) and by Lin and Shih (2022) and suggest that retrieving and connecting different information associated with *a priori* not-related concepts is not fully developed until late adolescence or early adulthood.

Although we did not observe different age-related patterns for each type of creativity, different trends were evident in the separate measures. The originality dimension of divergent creativity and the RAT measure of convergent creativity appeared to mature later than performance in the other measures. Therefore, it can be concluded that both convergent and divergent creativity continue to increase even into early adulthood, at least for some of the measures employed in this study.

The Mediating Role of Executive Functions in Age-Related Differences in Creativity

One main interest of the present study was to determine the extent to which executive and associative processes mediate the age-related changes observed in creativity. Our results indicated that executive functions and verbal fluency play a different role in mediating both types of creativity.

In convergent creativity, updating partially mediated age differences in RAT, as the age effect was reduced when both updating tasks were controlled for. These results provide additional evidence that updating plays a key role in explaining individual differences in convergent creativity performance (see also Zhao et al., 2021). Creative solutions in convergent tasks originate from the association of previously unrelated ideas or concepts retrieved from memory (Mednick, 1962). This requires a controlled search and selective retrieval in long term memory, as well as the ability to maintain and combine different information in WM. In this manner, WM updating would allow for the identification and maintenance of relevant information, limiting the search in long-term memory (Unsworth & Engle, 2007). With age, an enhanced updating ability would facilitate a more efficient search, which in turn, would lead to a greater probability of retrieving relevant ideas that would favor a creative solution. Furthermore, obtaining a solution also requires the continuous comparison of the candidate retrieved from long term memory with the different items maintained in WM. Accurate access to information held in WM contributes to age-related changes in updating (Linares et al., 2016) and also determines individual differences in WM capacity (Ecker et al., 2010). Therefore, the improvement with age of the ability to access information in WM would contribute to explaining the improvement on convergent creativity performance.

Updating assessed through the *n*-back task also partially mediated age differences on the flexibility dimension of divergent creativity. Süß et al. (2002) also reported that the variety of categories of ideas given in a series of creative tasks was related to performance in different updating tasks. This result suggests that the generation of varied responses benefits from the ability to simultaneously maintain a greater number of different ideas in WM, from which the most obvious could be replaced. Thus, improvements with age in the ability to maintain and substitute information in WM would enhance the probability to find more diverse solutions in divergent tasks.

Inhibition partially mediated age-related differences only in convergent creativity, measured with the RAT. This relationship occurred specifically with the go/no-go task, but not with the Stroop task. Our findings suggest that suppression of more accessible or automatic responses, and hence the most common solutions, would facilitate the access to less frequent, less obvious and more remote associated information (see also, Benedek, Franz et al., 2012; and Zabelina et al., 2012, for a similar interpretation). Importantly, the current study also shows that, as age increases, the ability to suppress dominant and automatic responses and avoid repetitive ones improves (Richardson et al., 2018), which, in turn, facilitates creative behavior.

Inhibition did not play a role in explaining age-related differences in divergent creativity, even though there was significant correlation among inhibition and flexibility and originality (as in other studies, see Palmiero et al., 2022 for a review). This finding is consistent with results from other studies that failed to find a relationship between inhibition and divergent creativity after controlling for educational level or age (e.g., Zabelina et al., 2019). Thus, although inhibition is related to both convergent and divergent creativity, this executive function only contributes to age-related differences in convergent creativity.

In our study, the shifting function did not mediate the relationship between age and creative performance. Only the indirect effect of age via plus-minus performance on creative fluency was found. In other studies, in which shifting was evaluated through classic executive tasks (Benedek et al., 2014; Zhao et al., 2021), no relationships were obtained either between the shifting function and creativity. However, Pan and Yu (2016), using tasks similar to those used here, found that shifting did predict performance on creative fluency and flexibility, but not originality. Although most of the evidence indicates that switching does not influence creativity, further research is needed to elucidate the conditions under which this executive function facilitates creative responses.

The Mediation of Verbal Fluency in Age-Related Differences in Creativity

Variation in verbal fluency fully explained the relationship between age and flexibility and originality. In the case of creative fluency, there was an indirect and positive age effect mediated by both phonological and semantic fluency and, and also a direct negative effect of age. This inconsistent mediation could be tentatively interpreted as reflecting two opposite age effects. With age, people recall more words, which contributes towards generating more creative responses; but, at the same time, individuals may become more cautious and evaluate more carefully the relevance of their answers, which contributes towards producing fewer solutions. These selected responses would be more original and from more disparate categories, as evidenced by the other creativity measures. With regard to convergent creativity, semantic and phonological fluency partially mediated the relationship between age and performance, but the direct effect of age remains significant once this mediating effect is taken into account.

Therefore, differences in accessing information in long-term memory contributed to explaining age-related differences in convergent and divergent creativity. Changes in semantic knowledge, both in the quantity and quality of associative links, as well as in the organization of conceptual representations vary markedly during development (Bjorklund, 1987; Sloutsky, 2015). As experience and knowledge increase, representations and associations between related concepts gain in complexity, favoring their semantic integration. This would also facilitate retrieval of more unusual information, leading to more creative responses.

The current results suggest a greater relevance of semantic over phonological fluency in age-related differences for all creativity measures. Previous research showed that creative quality in a divergent thinking task depends on both fluid retrieval ability and semantic knowledge (Beaty et al., 2014). In addition, it must be considered that fluency tasks require executive processes that monitor intrusions and response repetitions (Conway & Engle, 1994; Unsworth & Engle, 2007), whose development could also contribute to explaining the differences in creativity.

The Unique and Shared Contributions of Age, Executive Functions and Verbal Fluency to Creativity

The partitioning-variance method shed light on the the relative importance of executive functioning and fluency in explaining age-related differences in creativity. We found that differences in creativity were mediated by executive functioning and associative processing. The unique contribution of age to predicting creativity scores was very small. Indeed, nearly all of the variance in any of the creativity measures that could be accounted for by age was shared variance with executive and fluency measures. Consistent with the dual-processes theory (Beaty et al., 2014; Benedek & Jauk, 2018; Dygert & Jarosz, 2020; Gilhooly et al., 2007; Lee & Therriault, 2013), the contribution of each type of process to explaining the relation between age and creativity was different for each type of creativity. Specifically, age-related variation in convergent creativity was jointly accounted for by executive and associative processes, whereas age-related variation in divergent creativity measures was better explained by associative processes. As previously discussed, executive processes appear to have a lesser impact on divergent thinking compared to convergent thinking (Gerver et al., 2023), whereas retrieval mechanisms seem to be involved in both types of creativity. It is therefore logical that verbal fluency emerged as the main factor contributing to age-related variations in both forms of creativity.

The differential involvement of associative and executive processes, however, was not reflected in separate patterns of age-related differences for each dimension of creativity. Performance in some measures of divergent creativity (flexibility and fluency), peaked around secondary-school years, while others (originality and RAT) increased into young adulthood. It should be noted that performance on those mediators which accounted for age-differences in both types of creativity also improved across the entire age range of this study.

Limitations and Conclusions

The present study is not without its limitations. The cross-sectional design with three age cohorts allowed us to make inferences about changes in creativity across a wide range of ages. However, only concurrent relationships could be analyzed using this approach. A longitudinal study would reveal developmental trajectories of the different types of creativity, and would make it possible to control for previous relationships among the different variables and to determine whether early executive functioning and verbal fluency predicts creativity over time. Thus, further longitudinal studies should be conducted to confirm the causal roles of executive and associative processes in creativity. Another potential limitation of the current study is that it was focused on verbal creativity using cognitive tasks. The inclusion of other manifestations of creativity (for example, visual or graphic), as well as other more subjective measures (such as self-assessment or creative achievements in the real world) could provide more complete information (Rominger et al., 2022; Zabelina et al., 2019). Although we have employed the widely used Alternate Uses Task (AUT), the use of additional creativity tasks, more related to the product and the function of problems to be solved in real-world (see Cropley et al., 2017), would contribute towards gaining a better understanding of age changes in creativity.

An additional concern is the low reliability of some measures. Two executive tasks (Stroop and plus-minus) showed low reliabilities. This problem has been previously noted (e.g., Friedman & Miyake, 2004; Lee et al., 2009) and may be due to the fact that these executive measures rely on difference scores (e.g., Lee et al., 2009).

In the present study, this limitation may be ameliorated as there were other tasks for the same functions that showed adequate reliability. More problematic is the case of the originality index. Given that low reliability attenuates the correlation between the measures, some of the associations reported for originality could be higher using more reliable measures. Thus, further evidence is needed to better estimate the associations involving originality. Given that the low reliability of the originality measure has been reported previously (Barbot, 2019; Benedek et al., 2013; Reiter-Palmon et al., 2019), some effort should be put into improving its psychometric properties. For instance, increasing the number of stimuli (in addition to the brick and the newspaper) could contribute towards solving this pervasive limitation.

Only a few studies have jointly investigated the development of convergent and divergent creativity. The present results extend previous findings by providing evidence about the role of executive and associative processes in explaining age-related differences in convergent and divergent creativity. We conclude that the updating and inhibition executive functions, along with verbal fluency contribute to age changes in convergent creativity. In contrast, verbal fluency is the key factor explaining age differences in divergent creativity. Thus, the ability to efficiently retrieve information from memory turns out to be a crucial process underlying the age-related differences in both divergent and convergent creativity, while executive functions and retrieval are more determinant for age changes in convergent creativity.

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