Psychological Research
DOI 10.1007/s00426-017-0927-x

ORIGINAL ARTICLE

# Task intentions and their implementation into actions: cognitive control from adolescence to middle adulthood

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Received: 28 June 2017 / Accepted: 6 October 2017


**Abstract** Cognitive control processes involved in human multitasking arise, mature, and decline across age. This study investigated how age modulates cognitive control at two different levels: the level of task intentions and the level of the implementation of intentions into the corresponding actions. We were particularly interested in specifying maturation of voluntary task choice (intentions) and task-switching execution (their implementations) between adolescence and middle adulthood. Seventy-four participants were assigned to one of the four age groups (adolescents, 12–17 years; emerging adults, 18–22 years; young adults, 23–27 years; middle-aged adults, 28–56 years). Participants chose between two simple cognitive tasks at the beginning of each trial before pressing a spacebar to indicate that the task choice was made. Next, a stimulus was presented in one of the three adjacent boxes, with participants identifying either the location or the shape of the stimulus, depending on their task choice. This voluntary task-switching paradigm allowed us to investigate the intentional component (task choice) separately from its implementation (task execution). Although all participants showed a tendency to repeat tasks more often than switching between them, this repetition bias was significantly stronger in adolescents than in any adult group. Furthermore, participants generally responded slower after task switches than after task repetitions. This switch cost was similar across tasks in the two younger groups but larger for the shape than the location task in the two older groups. Together, our results demonstrate that both task intentions and their implementation into actions differ across age in quite specific ways.

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## Introduction

People often try to be more efficient by engaging in several activities at the same time. This human ability to multitask has been shown to rely on a dynamic interaction of different cognitive control processes (cf. Fischer & Plessow, 2015). Although the exact nature of the control mechanisms behind human multitasking is yet to be specified, various studies have informed us on different factors that might be important for this ability (Sanbonmatsu, Strayer, Medeiros-Ward, & Watson, 2013). For instance, how well we multitask seems to depend on our working memory capacity (Butler, Arrington, & Weywadt, 2011), our age (Wasylyshyn, Verhaeghen, & Sliwinski, 2011), or a combination of the two (Clapp & Gazzaley, 2012; Clapp, Rubens, Sabharwal, & Gazzaley, 2011). Considering that cognitive control mechanisms change across life span (Cepeda, Kramer, & de Sather, 2001; Craik & Bialystok, 2006; Zelazo, Craik, & Booth, 2004), the influence of age on multitasking might not come as a surprise. Interestingly, however, different parts of cognitive control arise, mature, and decline at different paces. There seems to be an important differentiation in how age influences

Published online: 13 October 2017

components of cognitive control mechanisms (Butler et al., 2011; Eich, MacKay-Brandt, Stern, & Gopher, 2016; Kievit et al., 2014). The aim of the current study was to further investigate how age—in the range of adolescents to middle-aged adults—interacts with two distinctive levels of cognitive control mechanisms involved in voluntary task switching. Specifically, we investigated age-related modulations of cognitive control at the level of intention formation (task choice) and at the level of subsequent implementation of these intentions into the corresponding actions (task execution).

Cognitive control processes involve mechanisms that allow us to keep the focus on task at hand despite possible internal or external distractions as well as mechanisms allowing us to change focus when needed (cf. Goschke & Dreisbach, 2008; Miller & Cohen, 2001). One way to investigate these mechanisms further in an experimental setting is to use a task-switching paradigm (for review, see Kiesel et al., 2010; Monsell, 2003). In this paradigm, participants are typically asked to switch between two (or more) simple cognitive tasks, for instance, switching between identifying shapes (task 1) and colours (task 2) of stimuli. Most often, bivalent stimuli are used that afford both tasks and, therefore, require some kind of indication of the currently relevant task. Usually, this is done either using external cues (e.g., Meiran, 1996; Poljac, Haan, & Galen, 2006) or predefined sequences of tasks (e.g., Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995). More recently, however, Arrington and Logan (2004, 2005) proposed a new paradigm, in which participants were required to choose between tasks, as if flipping a coin decided which task to perform. The idea behind this voluntary task-switching (VTS) paradigm was that it offers a method containing a more distinct top–down component than the cued procedures. In this way, the VTS paradigm introduced an intentional component in task switching (task choice) in addition to the previously used measure of its implementation into the corresponding action (task execution).

Both cued and VTS studies have demonstrated that although people are generally able to switch between tasks, they do so at a certain performance cost. Specifically, people tend to slow down and make more errors when switching between tasks as compared to repeating tasks. These switch costs seem to be one of the most robust findings in the task-switching literature, often assumed to reflect the ability to flexibly activate, and implement the appropriate task set (i.e., mental task representation). Switch costs are prone to both top–down (e.g., providing time for active task preparation; Koch, 2001; Liefooghe, Demanet, & Vandierendonck, 2009; Meiran, 1996; Rogers & Monsell, 1995) and bottom–up (e.g., activation of previously executed, currently irrelevant task; Allport et al., 1994; Hoffmann, Kiesel, & Sebald, 2003; Koch & Allport, 2006; Mayr & Keele, 2000; Poljac & Bekkering, 2009; Poljac, Koch, & Bekkering, 2009; Poljac & Yeung, 2014; Waszak, Hommel, & Allport, 2005; Yeung, 2010) effects. The influence of bottom–up effects, such as the effect of between-task interference, is rather interesting, given that switch costs are often considered as an index of top–down cognitive control.

One of the ways that between-task interference is suggested to be expressed in behaviour is the asymmetric switch cost (e.g., Yeung, 2010). It has been shown that when tasks differ in their relative strength,[1] they tend to leave distinct fingerprints on task-switching performance. Specifically, switching between a relatively easy and a relatively hard to execute task often results in larger switch costs when switching to the easy task as compared to switching to the harder task of a pair in both cued (Allport et al., 1994; De Jong, 1995; Ellefson, Shapiro, & Chater, 2006; Hübner, Kluwe, Luna-Rodriguez, & Peters, 2004; Yeung & Monsell, 2003a, b) and voluntary task-switching procedure (Millington, Poljac, & Yeung, 2013; Poljac, Poljac, & Yeung, 2012; Yeung, 2010). This somewhat contra-intuitive observation of relatively larger switch costs in the easier task has been explained in terms of differences in control biases between the two tasks (Gilbert & Shallice, 2002; Yeung & Monsell, 2003b). According to this view, control biases that are needed for correct task execution differ for tasks that vary in their relative strength. Therefore, for the harder task to be executed correctly, strong control biases are needed. Overcoming these stronger control biases when switching away from the harder task is reflected in behaviour as a larger switch cost in the task one switches to, that is, in the easier task. On the contrary, execution of the easier task generally requires little or no control bias, so that abandoning this task is not hard for the cognitive system, resulting in smaller switch costs when switching to the harder task. Altogether, this view suggests that asymmetric switch costs originate from asymmetric strengths of control biases required for correct execution of the two tasks (see also Bryck & Mayr, 2008).

Besides these similarities in findings between cued and VTS procedures in task execution, VTS studies have informed us about how people choose between two simple cognitive tasks. Interestingly, participants seem to demonstrate a tendency to repeat tasks more often than would be expected based on the instructions, clearly suggesting lack of optimal top–down control. Moreover, this

[1] Cognitive tasks can differ in their relative strength due to various factors, such as task difficulty, familiarity, and the amount of practice. A stronger task of a pair is the one that participants find easier to execute, because it is less difficult, more familiar, or more practiced. In the remainder of this paper, we used the terms *easier* and *harder* to refer to the *stronger* and the *weaker* task, respectively.

so-called repetition bias seems to become even stronger when the stimulus repeats from the previous trial (Mayr & Bell, 2006). Apart from this stimulus-repetition effect on task choice, relative difficulty between tasks seems also to affect participants' task choice. Specifically, a repetition bias asymmetry was observed in a similarly surprising way as above described switch-cost asymmetry: participants repeated the harder task more often than the easier task (Millington et al., 2013; Poljac et al., 2012; Yeung, 2010). Together, performance observed in studies using the VTS paradigm demonstrates a dynamic interaction between top–down and bottom–up processes, leaving specific fingerprints in both task intentions and their corresponding actions (Poljac & Yeung, 2014).

How task intentions (typically measured by means of task choice or the time taken for making the choice) relate to their subsequent translation into corresponding actions [typically measured as task performance in terms of reaction times (RT) and error rates] has been investigated in a couple of studies, with most of the studies providing evidence of dissociable influences on task choice and task execution (Arrington & Yates, 2009; Butler et al., 2011; Mayr & Bell, 2006; Millington et al., 2013; Poljac & Yeung, 2014; Yeung, 2010). For instance, Arrington and Yates showed a dissociation between task choice and task execution measures relative to three attentional networks indexed by the Attention Network Test (ANT; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005): alerting, orienting, and executive control. The authors observed that while alerting correlated with task performance, executive control networks correlated with task choice measures of multitasking behaviour. Empirical evidence has also been provided for common factors affecting both task choice and task execution. For instance, preparation time, which has extensively been shown to modulate task execution in task-switching studies (see Kiesel et al., 2010 for a review), seems also to affect task choice (e.g., Arrington & Logan, 2005). Although the relationship between processes behind task intentions (task choice) and their implementation into the corresponding actions (task execution) seems to be complex in nature, sufficient empirical evidence has been put forward in support of two distinct mechanisms. The current study investigated how task choice and task execution differ across age in voluntary task choice conditions.

Interest in a better understanding of how task-switching abilities change across age has produced numerous studies predominantly with cued task requirements. Although the findings reported in these studies were not always convergent, cued task-switching performance has been shown to differ across age (Cepeda et al., 2001; Verhaeghen & Cerella, 2002; Wasylyshyn et al., 2011). For instance, Cepeda and colleagues demonstrated that switching ability followed an inverted U-shape function, as it increased from childhood into young adulthood, stayed relatively stable across adulthood until the age of around 60 years, after which it started to decline. Later studies helped specifying the changes in task-switching performance across age in more detail (e.g., Kray, Eber, & Lindenberger, 2004; Lucenet, Blaye, Chevalier, & Kray, 2014; Reimers & Maylor, 2005). For instance, Reimers and Maylor showed that while switch costs were rather stable in their study, which included participants from 10 to 66 years of age, more general task-switching performance improved until the end of adolescence and then declined somewhat linearly across age. To measure this general task-switching performance, the authors compared participants' performance in single task blocks to that in mixed task blocks and observed a performance cost related to the mixed condition, sometimes also called global or mixing costs.[2] While switch costs are assumed to reflect ability to flexibly change between task sets (e.g., Rogers & Monsell, 1995), mixing costs are usually related to the ability to actively maintain task sets (e.g., Kray & Lindenberger, 2000).

Considering the current study focused on switch costs as a measure of task execution, it is important to mention that the actual cognitive mechanisms behind switch costs are still a matter of debate, as different studies have shown that switch costs are influenced by different experimental manipulations assumed to be related to for instance active task preparation, passive decay or active inhibition of now irrelevant task set, and memory (for an overview, see Kiesel et al., 2010; Liefooghe, Demanet, & Vandierendonck, 2010). Studies investigating these switch-cost-related mechanisms in non-adult populations are scarce (for a comprehensive review, see Cragg & Chevalier, 2012), leaving further specifications to future research. However, it is generally shown that task-switching ability is present in children as young as 6 years (Dibbets & Jolles, 2006), with switch costs staying rather stable across late childhood, adolescence, and young adulthood (e.g., Manzi, Nessler, Czernochowski, & Friedman, 2011). Furthermore, ageing studies have also provided evidence of stable switch costs in the elderly with both cued (e.g., Reimers & Maylor, 2005) and voluntary (Terry & Sliwinski, 2012; but see Butler & Weywadt, 2013) procedures.

[2] The differences in labelling reflect differences in research traditions: While the term mixing costs is mostly used within the research field of cognitive psychology, the term global costs is more common within the developmental and aging research fields. Please note that the two are not always measured in the same way. Mixing costs are typically measured as a difference in task repetition performance when comparing single tasks blocks with mixed task blocks, whereas global costs are mainly measured as a difference in performance between single task blocks and mixed task blocks, including the switch trials in the latter.

Studies investigating developmental changes in task choice behaviour using VTS paradigms are rare. The two ageing studies that focus on this matter showed similar patterns regarding age-related differences in task choice: a stronger repetition bias was observed in older adults compared to younger adults (Butler & Weywadt, 2013; Terry & Sliwinski, 2012). Butler and Weywadt extended this observation of a stronger repetition bias in older adults by showing that age might also modulate the actual way that task choices are made. Specifically, the authors showed that while the repetition bias was not modulated by stimulus-repetition effect in older adults, younger adults were more likely to repeat tasks when the stimulus repeated than when it changed. This suggests that whereas task choice strategy used by older adults was protected from external input, younger adults were sometimes relying on the availability of the external input for their task choice, such as bottom–up stimulus information (cf. Arrington, Weaver, & Pauker, 2010; Mayr & Bell, 2006). Accordingly, the repetition bias seems to occur when external stimulation is stronger than the internal aim.

Besides this bottom–up effect on task choice, two top–down accounts have been proposed for explaining the patterns of task choice observed in VTS: a memory-based approach, in which a representative random sequence is used as a comparison to the recent history of task choices based on which the next task choice is made (Arrington & Logan, 2005; see also Vandierendonck, Demanet, Liefooghe, & Verbruggen, 2012 for a long-term memory-based chain-retrieval model) and an inhibition-based approach, where each trial is treated as a discrete event, and active inhibition of the most recent task activation protects the system from perseverating (Mayr & Bell, 2006). These top–down views suggest that the repetition bias occurs when the top–down control mechanism fails. Developmental studies have informed us that both working memory (Zanolie & Crone, 2017) and inhibition (Schel, Scheres, & Crone, 2014) are mostly not yet fully developed in children and become more stable and mature across adolescence.

Therefore, empirical evidence for age-related modulations of task-switching abilities is abundant, predominantly generated in cued task-switching studies, but VTS studies have also offered some evidence. Specifically, developmental studies have demonstrated rather stable switch costs from late childhood on, while task choice behaviour can be expected to need more time to stabilise in adolescence due to the still developing mechanisms of memory and inhibition suggested to be involved in the way people make random task choice. The current study was designed to further investigate age-related effects on voluntary task switching, focusing specifically on task repetition bias as a measure of task intentions and switch costs as a measure of task execution.

The age range included here differs from typically used ranges in the developmental and ageing literature: our participants were divided into four age groups, with ages ranging from age 12–56 years. Recent studies have informed us that cognitive control mechanisms do not necessarily reach their optimal functioning in emerging adulthood (Wolff, Roessner, & Beste, 2016), leaving a possibility of so far undetected developmental changes across adulthood. In fact, a recent neuroimaging study focused on cognitive control capacities in 13–25-year-old individuals and demonstrated diminished cognitive performance under brief and prolonged negative emotional arousal in 18–21 years relative to adults over 21 (Cohen et al., 2016). The authors report that this inferior performance was accompanied by decreased brain activity in fronto-parietal circuitry known for being critical in cognitive control (e.g., Zanto & Gazzaley, 2013). This is an important finding as it suggests that the usual assumption of adulthood starting at the age of 18 mostly applied in scientific studies is not necessarily reflecting the true maturation of all aspects of cognitive control. In our study, the chosen age range allowed us to look at more gradual changes in maturation of cognitive control processes across age. Similar to the study of Cohen and colleagues, we divided our age groups into 12–17 years (adolescence), 18–22 years (emerging adulthood), 23–27 years (young adulthood), and 28–56 years (middle adulthood). We were particularly interested in how control processes behind task intentions and their implementation into actions in situation of voluntary task switching differ across this age range.

To investigate this, we used a voluntary task-switching paradigm, in which participants were asked to choose between a location task and a shape task on each trial, while keeping in mind to choose the two tasks about equally often and in random order (for similar procedures see Millington et al., 2013; Poljac et al., 2012). We recorded the time participants took to make their task choice as well as the actual task choices (task intentions), and their responding to the stimuli in terms of speed and accuracy (implementation of the intentions into corresponding actions). The two tasks we used here differed in their relative strength, with the location task being the easier task and the shape task being the harder task. This manipulation allowed us to look for differences in asymmetries that might arise in behavioural patterns across age range. Finally, we systematically manipulated stimulus repetitions to further specify age-related differences of stimulus-repetition effect on task choice, as previously reported by Butler and Weywadt (2013).

We expected to observe distinct age modulations for task choice and task execution behaviour. Specifically, while we expected switch costs to show a rather stable pattern across our four age groups, we expected repetition bias to differ between groups. Based on findings related to memory and inhibition, we expected adolescents to demonstrate a larger repetition bias than each of the three adult groups. Considering that no studies have been conducted yet that investigated task choice behaviour in VTS setting in this age range, it is possible that the typical pattern of repetition bias emerges later than adolescence, due to ongoing maturation of processes behind task choice behaviour (cf. Cohen et al., 2016). If task choice performance under conditions of random task choice requires more time to develop than is observed for memory and inhibition, then we expected repetition bias to be larger in both adolescents and emerging adults as compared to young and middle-aged adults.

## Methods

### Participants

Seventy-five participants, 12–56 years of age, took part in the study. One participant was excluded from all data analyses, as the mean RT was larger than three standard deviations above the mean. The remaining 74 participants (38 female) were divided into four groups based on their age (cf. Cohen et al., 2016): adolescents ($N = 20$, 12 female; age range = 12.2–17.4 years, mean age = 14.7, SE = 0.3), emerging adults ($N = 17$, 5 female; age range = 18.2–22.9 years, mean age = 20.9, SE = 0.4), young adults ($N = 19$, 12 female; age range = 23.2–27.7 years, mean age = 25.3, SE = 0.4), and middle-aged adults ($N = 18$, 9 female; age range = 28.2–56.4 years, mean age = 39.3, SE = 2.1). Eight participants were left-handed, two in each of the groups. All participants had normal or corrected-to-normal vision.

Participants were recruited through the Radboud Research Participation System (SONA systems) and flyers distributed at public (high) schools. They received a payment of 10 euro or course credits for the time invested. Prior to any testing, written informed consent was obtained from each participant. For the participants younger than 18 years of age, both parents provided their written informed consent in addition to the child's consent. The protocol was approved by the Review Board of Donders Centre for Cognition.

### Stimuli and tasks

Stimuli were three blue shapes: a triangle, a square, and a circle. In each trial, one of the shapes was presented inside a grid consisting of three adjacent boxes. At a viewing distance of approximately 1 m, the grid was 2.6° high and 7.4° wide. The presented stimulus approximately filled one box within the grid (see Fig. 1). Participants were instructed to respond by identifying either the shape (i.e., shape task) or the location (i.e., location task) of the presented stimulus after voluntarily choosing the shape or the location task. Participants were required to make this choice between tasks when a question mark was presented together with the empty grid.

The two tasks were uniquely mapped to participants' hands. Half of the participants responded to the shape by pressing keys with their left hand and to the location by pressing keys with their right hand. The other half of the participants responded with a reversed mapping. This allowed us to determine participants' task choices based on the hand they used to respond with. The actual response to either shape or the location of the stimulus was given by pressing a key with the index, middle, or ring finger of the respective hand. For the shape task, the stimulus–response (S–R) mappings were arbitrarily set. Specifically, we asked participants to use their leftmost, middle, and rightmost finger of the appropriate hand for circle, square, and triangle, respectively. For the location task, however, the S–R mappings were directly linked as the leftmost, middle, and rightmost fingers were used to indicate the left, centre, and right boxes, respectively.

### Procedure

Participants first got acquainted with the shape and location tasks by practicing each of them separately for 20 trials. Next, they practiced switching and making choices between the two tasks for two blocks of 20 trials each. After the practice part, the experimental part started, consisting of eight blocks of 60 trials each. The total number of experimental trials was hence 480 per participant. Across the experimental trials, stimuli were presented quasi-randomly. Specifically, the two stimulus dimensions were systematically varied, such that between two successive trials, stimuli either fully repeated (same shape presented in same location), partially repeated in one of the two ways (either same location or same shape), or repeated not at all (different shape in different location). Each of the four possibilities of stimulus repetition occurred equally often.

Each trial began with an empty grid accompanied by a question mark (see Fig. 1 for a schematic overview of trial events). As such, the question mark served as a cue to participants, indicating that they needed to make their task choice for that trial. Specifically, they were instructed to voluntarily choose between shape or location tasks on each trial while choosing the two tasks around equally often and in random order (cf. Arrington & Logan, 2004). Once the task choice was made, they pressed the spacebar to indicate

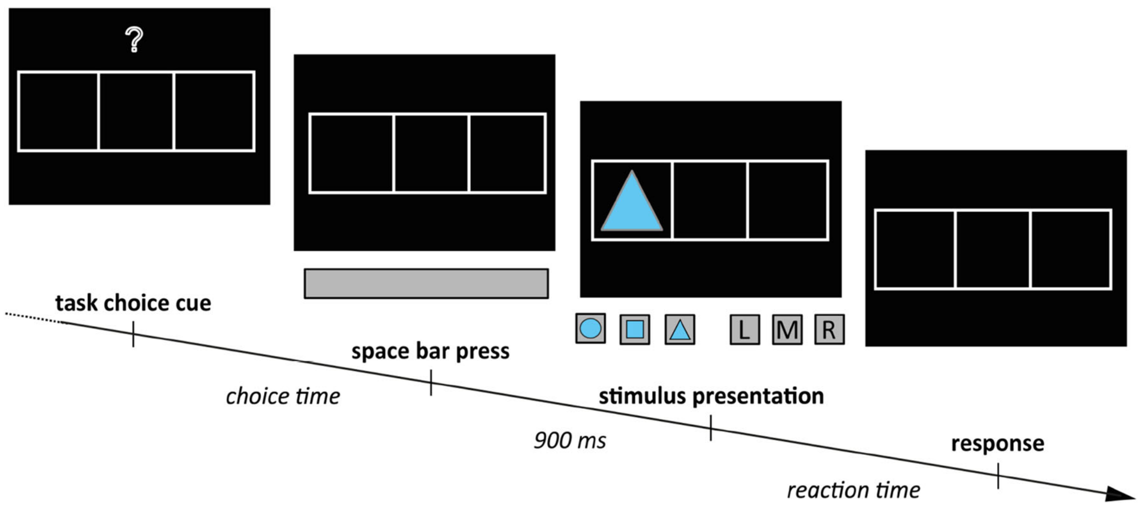


**Fig. 1** Schematic representation of the trial events. A trial started with the presentation of a question mark right above a grid, which was present on the screen during the entire trial. The question mark was a cue to the participants to make a deliberate choice of tasks for that trial and then to press the spacebar indicating that the task choice was made. The time needed for making this task choice (i.e., choice time) was measured as the interval between the presentation of the question mark and the space-bar press. The stimulus appeared 900 ms after the spacebar was pressed, with stimuli consisting of geometric figures appearing in one of the three possible locations in the grid. In this way, each stimulus afforded two possible tasks: shape (circle/square/triangle) and location (left/middle/right). The tasks were mapped separately to the two hands, and the participants responded by pressing a key. In the example illustrated here, the left hand is used to respond to the shape (circle, square, triangle) and the right hand to the location of the stimulus (*L* left, *M* middle, *R* right). The correct response for the depicted example would be pressing the right most key with the left index finger for the shape task or pressing the left most key with the right hand for the location task. After the response was given, the grid was emptied for 300 ms, followed by the question mark indicating the start of the next trial

that they had made their choice, without explicitly indicating *what* that particular task choice was (cf. Millington et al., 2013; Poljac et al., 2012). Participants were requested to hit the spacebar with both their thumbs as soon as they had made their task choice. Hitting the spacebar removed the question mark but not the grid, which stayed empty for an interval of 900 ms. After this interval, a stimulus appeared in one of the three locations within the grid and remained on the screen until a response was given. The response triggered emptying the grid for 500 ms, after which the question mark appeared again. This was the cue for participants that the new trial had started and that they needed to make their next task choice. Participants were encouraged to make deliberate task choices and take the time needed for making their choice before hitting the spacebar to do so.

At the end of each block, participants were reminded to respond both as quickly and as accurately as possible and to follow the instructions about equal task distribution and 'random' switching as described above. In addition, feedback on performance in the block they just finished was given by summarising their individual average response and choice times, counts of errors, counts of choices for each of the tasks, and counts of switch and repeat trials. Finally, participants were encouraged to use the time between blocks to rest if needed.

## Design

The current study included three within-subjects variables and one between-subjects variable. The within-subjects variables were Task (location/shape), Transition (switch/repeat) and Stimulus Repetition (full/location/shape/none), whereas the between-subjects variable was Age (adolescents/emerging adults/young adults/middle-aged adults). Whether the current trial was considered a switch or a repeat trial was determined by comparing the current task with the previously performed task. Furthermore, the four possible stimulus-repetition types occurred equally often across trials.

We measured the behaviour related to participants' task choice that the participants made as well as their responses to the presented stimuli. Two measures related to task choice were used. First, we calculated percentages of task repetitions. This measure was then submitted into a $2 \times 4 \times 4$ (Task × Stimulus Repetition × Age) repeated measures ANOVA. Second, we measured the time participants took to make their choice of tasks. Choice times were then submitted to a$2 \times 2 \times 4$ (Task × Transition × Age) repeated measures ANOVA, which was also applied on the two measures used for stimulus-related behaviour: mean reaction times and error rates. To calculate error rates, we first specified the hand used to respond to the target stimulus. Given that left and right hands were uniquely linked to the tasks, knowing the hand used to respond allowed us to identify the intended task, and hence the correct finger for the specific stimulus. Accordingly, error trials were defined as those in which the participant responded with the incorrect finger of the hand used for the intended task. We then calculated error rates for each of the Task × Transition conditions per participant as a relative measure between the number of errors made within a specific condition and the total number of times that the respective condition was chosen by the participant.

## Results

### Percentages of task repetitions

To investigate whether task choices were mediated by bottom–up stimulus information and age, percentages of task repetitions were submitted into a 2 × 4 × 4 (Task × Stimulus Repetition × Age) repeated measures ANOVA. The analysis of stimulus-repetition effect on task choice was possible because of the specific type of the VTS paradigm used here: while the participants were required to make their choice of task deliberately before pressing the spacebar, they were not asked to specify their actual task choice before responding to the stimulus. In this way, participants might possibly have in some cases ignored their initial intention due to interfering factors. Therefore, to investigate how well the participants were following their initial intentions, we tested how stimulus repetition was affecting task choices. It has already been shown that the initial intention may be ignored when the stimulus repeats across trials (Mayr & Bell, 2006). The idea behind this effect is that deliberately choosing between tasks before stimulus presentation should protect the formed intention and hence the eventual task choice from any stimulus-related manipulation introduced in the design. If, however, the initial intention is not stable enough, it is possible for the stimulus to affect the eventual task choice, such as observed for stimulus repetitions.

The analysis of percentages of task repetitions revealed three significant main effects. First, a main effect of Task was observed, $F(1,70) = 36.67$; $p < .001$, with participants repeating the shape task more often ($M = 60.9\%$, SE = 1.4) than the location task ($M = 57.5\%$, SE = 1.5). Second, a main effect of Stimulus repetition, $F(3,68) = 16.77$; $p < .001$ was observed. Participants repeated tasks more when stimulus features repeated fully ($M = 61.6\%$, SE = 1.4), or partially (stimulus location repetition, with $M = 60.1\%$, SE = 1.6; and stimulus shape repetition, with $M = 58.9\%$, SE = 1.5) across trials, as compared to no stimulus repetition ($M = 56.2\%$, SE = 1.5). Simple contrast analyses confirmed a significant difference between full stimulus repetition and all other levels of Stimulus repetition, with $F(1,70) = 5.04$; $p = .028$, $F(1,70) = 12.18$; $p = .001$, and $F(1,70) = 49.72$; $p < .001$, for the comparison between full stimulus repetition and stimulus location, stimulus shape, and no stimulus repetition, respectively. Furthermore, the stimulus did not need to be fully repeated across trials to increase the tendency of task repetitions, as both partially repeating stimulus features, that is, stimulus location repetition ($F(1,70) = 28.46$; $p < .001$) and stimulus shape repetition ($F(1,70) = 12.95$; $p = .001$), significantly increased the tendency to repeat tasks as compared to no stimulus-repetition condition. Simple contrasts for the two types of the partial stimulus repetitions revealed no significant difference between them, $F(1,70) = 2.55$; $p = .115$.

Third, a significant main effect of Age was observed, $F(3,70) = 2.78$; $p = .047$. Simple contrasts revealed that, while the percentages of task repetitions did not significantly differ among the three adult groups ($F$s < 1), adolescents ($M = 66.0\%$, SE = 2.7) repeated tasks significantly more often than emerging adults ($M = 55.5\%$, SE = 3.0), with $F(1,35) = 6.83$; $p = .013$. Furthermore, adolescents also repeated tasks more often than young adults ($M = 57.4\%$, SE = 2.8), and middle-aged adults ($M = 58.0\%$, SE = 2.9), with $F(1,37) = 3.64$; $p = .064$ and $F(1,36) = 4.08$; $p = .051$, respectively.[3]

Finally, no significant interactions between Task and Age nor between Stimulus repetition and Age was observed ($F$s < 1), indicating that participants' task repetitions were modulated by tasks and stimulus repetitions in a similar way across age (see Table 1).

### Choice time

To analyse the time participants took to make their task choice, we calculated the mean time between the presentation of the question mark (cue for making a task choice) and the spacebar press (indication that a task choice was made). The data were first cleaned from the first trials of each block, which was 592 trials across all participants, that is, 1.7% of all trials. These trials were excluded, because they were preceded by a self-paced break between the experimental blocks and were thus hard to classify as either a task switch or a task repetition. Furthermore, excluding the outliers—which were defined per participant as latencies deviating more than 3 SDs from the mean latency of each of the conditions—resulted in excluding

[3] This observation of age differentiation for percentages of task repetitions was confirmed when using Age as continuous variable: Spearman's rank-order correlation reveled that percentages of task repetitions had a tendency to decrease with age ($r_s = -.22$, $p = .056$).

**Table 1** Percentages of task repetitions (%) and standard errors in parentheses for each age group (adolescents/emerging adults/young adults/middle-aged adults) as a function of stimulus repetition (none/location/shape/full) and task (location/shape)

| Age group | Stimulus repetition | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | None | | Location | | Shape | | Full | |
| | Location | Shape | Location | Shape | Location | Shape | Location | Shape |
| Adolescents ($N = 20$) | 59.9 (3.0) | 64.3 (3.3) | 64.2 (3.4) | 68.1 (3.1) | 65.9 (2.9) | 66.6 (3.1) | 67.7 (3.1) | 70.3 (2.8) |
| Emerging adults ($N = 17$) | 50.4 (3.3) | 55.1 (3.3) | 55.1 (3.7) | 56.1 (3.4) | 52.9 (3.2) | 58.1 (3.3) | 56.7 (3.4) | 59.7 (3.0) |
| Young adults ($N = 19$) | 55.2 (3.1) | 53.9 (3.1) | 55.8 (3.5) | 60.4 (3.2) | 54.8 (3.0) | 60.2 (3.1) | 57.9 (3.2) | 61.2 (2.8) |
| Middle-aged adults ($N = 18$) | 53.5 (3.2) | 57.2 (3.2) | 58.5 (3.6) | 62.4 (3.3) | 53.7 (3.1) | 58.5 (3.2) | 57.4 (3.3) | 61.8 (2.9) |
| All participants ($N = 74$) | 54.7 (1.6) | 57.6 (1.6) | 58.4 (1.8) | 61.7 (1.6) | 56.8 (1.5) | 60.9 (1.6) | 59.9 (1.6) | 63.2 (1.4) |

additional 595 trials, which was also 1.7% of all trials. Together, the exclusion criteria we applied resulted in elimination of 1187 trials, which was 3.3% of all data.

The mean choice time was then submitted into a 2 × 2 × 4 (Task × Transition × Age) repeated measures ANOVA, which revealed only a significant main effect of Task, $F(1,70) = 5.39$; $p = .023$. Specifically, the participants took on average more time to choose the harder shape task ($M = 295$ ms, SE = 24.0) than the easier location task ($M = 286$ ms, SE = 22.2). No other main effects or interactions were significant, implying that choice time data did not differentiate between the four age groups.

## Reaction times

Similar to the choice time data analysis, reaction times data were cleaned by excluding the first trials of each block (1.7% of all trials) and the outliers (an additional 484 trials, that is 1.4% of all trials). Furthermore, error trials and trials following errors were excluded, comprising a total of 2111 trials across participants, that is, 5.9% of all trials. This resulted in a total of 9.0% of all trials being excluded.

Mean RTs were then submitted into a 2 × 2 × 4 (Task × Transition × Age) repeated measures ANOVA, which revealed a main effect of Task ($F(1,70) = 312.75$; $p < .001$) and Transition ($F(1,70) = 80.99$; $p < .001$). As expected, the shape task was the harder task for participants to perform, as they were on average slower performing the shape task ($M = 691$ ms, SE = 15.9) than the location task ($M = 529$ ms, SE = 13.9). In addition, participants demonstrated a significant switch cost of 55 ms on average, with slower RTs after a task switch ($M = 638$ ms, SE = 15.8) than after a task repetition ($M = 583$ ms, SE = 13.2). This switch cost did not differ between the age groups, with $F < 1$, for Transition × Age.

Importantly, a significant interaction was observed between Task, Transition, and Age, $F(3,70) = 3.48$; $p = .020$.[4] Further investigation of the Task × Transition interaction between the groups revealed that while this interaction did not significantly differ between the youngest two groups nor between the oldest two groups ($F$s $< 1$), the interaction differed significantly between the two younger groups compared to the two older groups. Specifically, the Task × Transition interaction in adolescents differed from that observed in young adults ($F(1,37) = 5.86$; $p = .020$) and middle-aged adults ($F(1,36) = 5.37$; $p = .026$). In a similar vein, the Task × Transition interaction in emerging adults differed from those observed in young adults ($F(1,34) = 4.48$; $p = .042$) and middle-aged adults ($F(1,33) = 4.25$; $p = .047$). In addition, testing the Task × Transition interaction for each of the four age groups revealed that while this interaction was not significant in either adolescents ($F(1,19) = 1.43$; $p = .25$) or in emerging adults ($F < 1$), it reached significance in both the young ($F(1,18) = 5.06$; $p = .037$) and middle-aged adults ($F(1,17) = 5.18$; $p = .036$). Specifically, as shown in Table 2, in both adolescents and in emerging adults, switch costs were numerically larger when switching to the location task (switch costs = 58 and 57 ms, respectively) than when switching to the shape task (switch costs = 39 and 50 ms, respectively), while in the young and middle-aged adults, the pattern was reversed, with switch costs being significantly larger in the shape task (switch costs = 69 and 80 ms, respectively) than in the location task (switch costs = 34 and 51 ms, respectively). Together, reversal in direction of switch-cost asymmetry was detected, with adolescents and emerging adults demonstrating numerically larger switch costs when switching to the location

[4] When correcting for possible baseline differences between the groups by applying the logarithmic transformation of the RT data, which is a data correction method often used in studies on aging (cf. Kray & Lindenberger, 2000; Mayr, 2001), we observed that the three-way interaction between Task, Transition, and Age became marginally significant, with $F(3,70) = 2.39$; $p = .076$.

**Table 2** Mean RTs (ms) and standard errors in parentheses for each age group (adolescents/emerging adults/young adults/middle-aged adults) as a function of task (location/shape) and transition (switch/repetition)

| Age group | Location | | Shape | |
|---|---|---|---|---|
| | Switch | Repetition | Switch | Repetition |
| Adolescents ($N = 20$) | 592 (30.2) | 534 (24.5) | 725 (34.0) | 686 (28.5) |
| Emerging adults ($N = 17$) | 535 (32.7) | 478 (26.6) | 665 (36.8) | 615 (30.9) |
| Young adults ($N = 19$) | 541 (30.9) | 506 (25.2) | 733 (34.8) | 664 (29.3) |
| Middle-aged adults ($N = 18$) | 548 (31.8) | 497 (25.9) | 761 (35.8) | 681 (30.1) |
| All participants ($N = 74$) | 554 (15.7) | 504 (12.8) | 721 (17.7) | 662 (14.9) |

task than when switching to the shape task, whereas both young and middle-aged adults had significantly larger switch costs when switching to the shape task than when switching to the location task.[5]

Finally, the main effect of Age was not significant ($F < 1$), suggesting that the two tasks were around equally demanding for the participants in the four age groups.

### Error rates

Similar to the RTs, mean error rates were submitted into a 2 × 2 × 4 (Task × Transition × Age) repeated measures ANOVA, which again revealed a main effects for Task ($F(1,70) = 78.66$; $p < .001$) and Transition ($F(1,70) = 39.29$; $p < .001$). The participants were on average less accurate performing the shape task ($M = 4.5\%$, SE = 0.3) than performing the location task ($M = 1.8\%$, SE = 0.2) and after a task switch ($M = 3.9\%$, SE = 0.3) than after a task repetition ($M = 2.4\%$, SE = 0.2). No other main effects or interactions were significant, implying that error rates did not differentiate between the four age groups in our study.

## Discussion

The current study was designed to investigate how cognitive control processes involved in voluntary task switching differ across age, from adolescence to middle adulthood. The findings demonstrate specific age-related differences of cognitive control at both the level of task intentions (task choice) and the level of their implementation into the corresponding actions (task execution). For task intentions, we observed a task repetition bias in all age groups, with this tendency to keep repeating tasks being the strongest in adolescents as compared to all of the adult groups. Furthermore, the ways that the two tasks showed asymmetries in the observed repetition bias (stronger repetition bias in the relatively harder task) did not differ across the age groups. For the implementation of task intentions into the corresponding actions, however, we detected a rather different pattern: while the switch costs observed in the current study did not differentiate between the age groups, their asymmetry showed particular age-related patterns. Specifically, we observed a trend towards a reversal in direction of switch-cost asymmetry when comparing the two youngest groups with the two oldest ones: whereas adolescents and emerging adults demonstrated numerically the typical pattern of larger switch costs in the easier task (though not reaching significance), young and middle-aged adults showed larger switch costs for the harder task than for the easier task. In what follows, we discuss the implications of these findings for existing ideas of age modulation of cognitive control for intentions and actions.

### Task intentions across age

Repetition bias was observed in all of the age groups included in the current study, demonstrating a robust tendency of the participants to repeat tasks more often than to switch between them. As expected, however, the repetition bias was significantly stronger in adolescents than in adults. This observation extends previously reported age-related sensitivity of the repetition bias in ageing studies (Butler & Weywadt, 2013; Terry & Sliwinski, 2012). Specifically, Terry and Sliwinski showed that older adults (74–87 years of age) were inclined to repeat tasks more than younger adults (18–21 years of age), an observation later replicated by Butler and Weywadt, with a slightly different age range for younger (18–24 years) and older (61–88 years) adults. The current study demonstrates in addition that adolescents perseverate more in their task choices than any of the adult groups, who showed a rather stable repetition bias among themselves. These findings together suggest that the repetition bias is modulated by age, following an U-shaped pattern, with both adolescents (ca. 12–18 years of age) and older adults (ca. 60 + years of age) showing a stronger tendency to persevere in their task choice than other adults (ca. 18–60 years of age).

A plausible explanation for age-related influences on the repetition bias comes from the suggestion that the

[5] The observations of age-related changes in switch costs and switch cost asymmetry was confirmed when using age as continuous variable: Spearman's rank-order correlation reveled that while switch costs were stable across age ($r_s = .10$, $p = .376$), switch cost asymmetry declined with age ($r_s = -.26$, $p = .023$).

repetition bias is related to the efficiency of top–down control processes involved in the voluntary selection of task goals. Specifically, it has been suggested that participants tend to repeat tasks because at the moment of task choice it is the task chosen on the previous trial that is still the most active one (Mayr & Bell, 2006). Mayr and Bell suggested that one needs to inhibit the activated task in order to overcome the repetition bias, meaning that task selection depends on top–down control processes such as inhibition counteracting the automatic tendency to repeat tasks (Demanet, Verbruggen, Liefooghe, & Vandierendonck, 2010). The idea of inhibition processes being critical for regulating task repetition behaviour in VTS fits nicely with the observation that, in our study, the repetition bias was the strongest in adolescents: many studies have shown that the ability to inhibit prepotent action develops across adolescence during which it becomes more stable and mature as one approaches late adolescence at around 18 years of age (see Schel et al., 2014 for a review). The idea that inhibition processes are behind the greater repetition bias is also in line with the observation of an increased repetition bias in the elderly (Butler & Weywadt, 2013; Terry & Sliwinski, 2012) as many studies have provided empirical evidence for difficulties with inhibitory control in older age (e.g., Butler & Zacks, 2006).

Empirical evidence challenging this idea of age-related inhibitory-control differences being responsible for the observed greater repetition bias in adolescents compared to adults comes from studies looking at age-related modulations of $n-2$ task repetition costs in task switching (e.g., Lawo, Philipp, Schuch, & Koch, 2012; Mayr, 2001; Schuch, 2016; Schuch & Konrad, 2017). The typical findings of these studies, which require participants to switch between three simple cognitive tasks, is that performance on a task (e.g., Task A) is slowed down when this task has just recently been abandoned (i.e., Task A–Task B–Task A sequence compared to Task C–Task B–Task A sequence). This $n-2$ task repetition cost has been explained in terms of task-set inhibition being implemented on the no-longer relevant task when switching to a new task to allow for the required task switch. Consequently, switching back to a just abandoned task should then result in decreased performance, because inhibition persists over time and this residual inhibition needs to be overcome (for a review, see Koch, Gade, Schuch, & Philipp, 2010). The $n-2$ repetition cost has been shown to be rather stable across age, when comparing young and old adults (Lawo et al., 2012; Mayr, 2001; Schuch, 2016) or when comparing children and young adults (Schuch & Konrad, 2017). Together, these studies indicate that the idea of differences in inhibitory control accounting for age-related repetition bias differences is not straightforward. It is of course possible that age modulates some aspects of inhibition that are specifically related to cognitive processes behind task choice, which then becomes evident in repetition bias differences but not in $n-2$ task repetition costs. Such assumptions on different types of inhibition processes or different functions of inhibition, however, require further testing.

Another possible explanation for age-related dependency of the repetition bias could be given in terms of working memory development. It has been suggested that task choice in VTS is made based on a representative random sequence that is used as a comparison to the recent history of task choices based on which the next task choice is made (Arrington & Logan, 2005; see also Mittelstädt, Dignath, Schmidt-Ott, & Kiesel, 2017). Developmental studies have shown that working memory is usually underdeveloped in children and becomes more stable and mature across adolescence (Zanolie & Crone, 2017). Specifically, working memory related to item manipulation rather than item maintenance seems to need time to develop in adolescence (Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006). Of course, the role of ageing in working memory abilities has been largely established (for a current review see Park & Festini, 2017), suggesting that similar to inhibition, working memory could account for increased repetition bias in adolescence as observed in our study and previously reported increased repetition bias in elderly participants.

Perhaps the most intuitive explanation for the repetition bias could be given in terms of effort avoidance. According to this logic, participants opt for task repetitions more often because task repetitions are relatively easier to execute than task switches (e.g., Kool, McGuire, Rosen, & Botvinick, 2010). However, our observation of a stronger repetition bias for the harder shape task contradicts this simple explanation: if the task choice was driven by effort avoidance, then we would expect the relatively easier task of the pair to be chosen more often. A similar repetition bias asymmetry showing a stronger tendency to repeat the relatively harder task of a pair has already been reported in voluntary task-switching studies (Millington et al., 2013; Poljac et al., 2012; Yeung, 2010). Our data show that this relatively small but consistent finding of repetition bias asymmetry is stable across all age groups investigated here.

Repetition bias asymmetry has often been used as an example of expression of between-task interference in task choice behaviour (Millington et al., 2013; Yeung, 2010). Specifically, it has been suggested that participants keep on repeating the harder task more due to asymmetric control biases between the two tasks, as one needs to exert more control over the relatively harder task in order to execute this task correctly, whereas less cognitive control is required for the correct execution of the easier task. Accordingly, persisting biases towards the harder task make switching away from this task more difficult, resulting in a surprising preference for continuously performing the harder task. Our observation of a small but consistent repetition bias asymmetry seems to be in line with this idea of between-task interference contributing to the repetition bias. However, as the repetition bias asymmetry observed in our study did not differ across age groups, such a between-task interference account may sufficiently explain the larger general repetition bias observed in adolescents. So, although between-task interference seems to have influenced task choice behaviour in all of our investigated age groups, it seems not to offer an explanation for the stronger repetition bias in adolescents.

In a similar fashion, another bottom–up explanation for the repetition bias seems also to fail to explain our finding of the stronger repetition bias in adolescents. It has been suggested that the repetition bias might occur when external input is stronger than the internal aim. Empirical support for this idea comes from studies investigating the so-called stimulus-repetition effect in VTS (Arrington et al., 2010; Butler & Weywadt, 2013; Mayr & Bell, 2006), showing that participants are more likely to repeat the previous task if the stimulus repeats from the previous trial. In the current study, the effects of stimulus repetition on task choice were also evident. So, rather than following the initial intention in each trial, our participants were inclined to conduct behaviour afforded by the stimulus in some of the trials. Importantly, however, the way that stimulus repetition affected repetition bias did not differ between the age groups in our study. This observation suggests that although a stimulus-repetition effect significantly contributed to the repetition bias in general, the stronger repetition bias observed in adolescents as compared to adults seems not to originate from stimulus-related effects.

Together, both between-task interference and stimulus repetition have significantly affected task choice behaviour in all age groups of the current study. Importantly, however, these two mechanisms seem not to be able to explain the stronger repetition bias observed in adolescents. Specification of the mechanisms behind this observation would require further studies. A possible way to proceed is to look for an explanation at the level of top–down failure in adolescents due to for instance still developing working memory capacities or inhibition. In fact, this approach sounds sensible considering that it has been shown that cognitive control processes typically require time to develop during adolescence (for a review see Best & Miller, 2010).

### Task execution across age

Our findings demonstrate robust switch costs that were stable across the four age groups. This observation is in line with some other ageing studies using instructed (Kray & Lindenberger, 2000; Mayr, 2001; but see Kray, 2006; Meiran, Gotler, & Perlman, 2001) or voluntary (Terry & Sliwinski, 2012; but see Butler & Weywadt, 2013) task-switching procedures. In addition, this observation shows that, similar to the observations reported in some studies using instructed task-switching procedures (e.g., Reimers & Maylor, 2005), switch costs in studies using voluntary task-switching procedure are stable across adolescence and emerging adulthood. Different theories have been proposed to account for processes allowing for switching between task sets as well as for control mechanisms reflected in switch costs, such as for instance the task-set reconfiguration explanation of switch costs (see Kiesel et al. for an overview). Our findings suggest that these control mechanisms seem to be producing comparable behaviour from adolescence to middle adulthood.

However, while switch costs seemed not to differ between adolescents and any of the adult groups in our study, switch-cost *asymmetry* demonstrated some interesting age-specific patterns. Specifically, we observed a trend towards a reversal in direction of switch-cost asymmetry when comparing adolescents and emerging adults with young and middle-aged adults. This observation is remarkable for two different reasons. First, it shows differentiation between the two younger and the two older groups in our study. Second, the direction of the observed asymmetry in the older two groups is opposite to the one considered being a classic example of switch-cost asymmetry. In what follows, we discuss the switch-cost asymmetry and its seemingly peculiar direction observed in the current study, followed by a discussion on its possible implications for a better understanding of age-related differences in task-switching behaviours.

Classical switch-cost asymmetry is considered to include larger switch costs when switching from a relatively harder task to a relatively easier task of a pair and has been reported in studies using predefined (Allport et al., 1994; De Jong, 1995; Yeung & Monsell, 2003a, b) and voluntary task-switching procedures (Millington et al., 2013; Poljac et al., 2012; Yeung, 2010). These asymmetric switch costs have been explained in different ways, such as, for instance, being generated by differences in positive and negative task priming (Allport et al.), relative difference in activation (Gilbert & Shallice, 2002; Yeung & Monsell, 2003b) or inhibition of tasks (Arbuthnott, 2008; Jost, Hennecke, & Koch, 2017), differences in long-term memory representations (Bryck & Mayr, 2008), or as a result of sequential effects of difficulty (Schneider & Anderson, 2010). The classical finding is, however, far from universal. Some studies have demonstrated that an asymmetry might occur in conditions where no task switching is required (Bryck & Mayr, 2008) or even with tasks that do not differ in their objective, that is, performance based difficulty (Barutchu, Becker, Carter, Hester, & Levy, 2013). Furthermore, the occurrence of asymmetric switch costs seems to depend on the instructions used (Liefooghe et al., 2010) or might not be detected at all (Monsell, Yeung, & Azuma, 2000). The diversity of these reports makes it hard to offer a sensible explanation of the reversed switch-cost asymmetry in the two older groups in our study. Nevertheless, our findings suggest that switch-cost asymmetry might be an interesting measure of age-related differences in implementations of task intentions into the corresponding actions.

Not many studies have used VTS procedures so far when investigating age-related differences, and those that we have discussed before, have not looked at switch-cost asymmetries. Studies investigating voluntary switching between dominant and non-dominant language may add some additional insights. These studies reported no switch-cost asymmetry for language switching when testing children (Gross & Kaushanskaya, 2015) or older adults (Gollan & Ferreira, 2009, Experiment 3). Gollan and Ferreira suggested that the reason why they failed to replicate asymmetric language-switching costs previously reported in studies using cued task-switching procedures (Costa & Santesteban, 2004; Meuter & Allport, 1999; Philipp, Gade, & Koch, 2007) might be due to differences between the mechanisms underlying the two task-switching procedures. This explanation is empirically supported by neuroimaging studies providing evidence for differentiation of control mechanisms involved in voluntary and cued task switching (Forstmann, Brass, Koch, & von Cramon, 2006). Following this line of reasoning, one could suggest that the reversed switch-cost asymmetry observed in our study might be due to the specifics of the VTS paradigm applied here. This explanation is, however, difficult to accept given that some previous studies using a VTS paradigm similar to the one used here have reported classical switch-cost asymmetries (Millington et al., 2013; Poljac et al., 2012; Yeung, 2010).

The question that remains to be addressed is: what is the cognitive mechanism that can account for the observed change in asymmetric switch costs across age. The current study clearly does not allow for any specification of the underlying mechanisms, but a possibly interesting explanation arises from an observation of the reversal of the classical switch-cost asymmetry by reducing the between-task interference by either delaying the processing of the easier task or by separating the response sets of the tasks used (Yeung & Monsell, 2003b). Accordingly, one could say that the classic switch-cost asymmetry (larger switch costs when switching to the easier task of the pair) occurs in situations of high between-task interference, whereas the more intuitively expected asymmetry (larger switch costs when switching to the harder task of the pair) happens in conditions in which between-task interference is lowered. Following this, we could speculate that the classic switch-cost asymmetry (typically observed in student populations) is a reflection of a still developing control mechanism that manages between-task interference. At this stage, it is hard to put forward cognitive mechanisms directly responsible for the observed age-related switch-cost asymmetry modulations. Clearly, further studies are needed to help us specify the actual cognitive mechanisms behind switch-cost asymmetries and improve our understanding of their development across age. What our study allows us to say is that our findings of age-specific patterns in switch-cost asymmetry suggest that in addition to investigating switch costs, their asymmetries might also be an informative measure for a better understanding of how translation of task intentions into their corresponding actions varies across age in VTS situations.

Two additional points deserve to be mentioned here. The first point relates to the number of participants included in the study. It is possible that the numerical switch-cost asymmetry in adolescents and emerging adults failed to reach statistical significance due to an insufficient number of participants. For this reason, we cannot exclude the possibility that the age differences reported here are less pronounced than they would have been if more participants were included. Given the effect sizes found for young (partial $\eta^2 = .219$) and middle-aged adults (partial $\eta^2 = .233$) in our study, and assuming an alpha level of .05 and a statistical power of 80%, 31 participants are needed per group for switch-cost asymmetry to reach statistical significance (G*Power 3.1.9.2 software, Faul, Erdfelder, Lang, & Buchner, 2007), whereas our four groups comprised 17–20 participants.

The second point is a methodological point and considers the type of VTS paradigm used in the current study. In our VTS paradigm, the choice of tasks was not explicitly indicated by participants. Accordingly, we derived participants' task intentions from the hand they used to reply. In such a paradigm, it is possible that the participants did not always follow their task intentions established before a stimulus was presented. However, given that the error percentages were generally low (3%), it is reasonable to expect that the trials in which intention following was disrupted were not frequent. Also, it has been shown that the space-bar VTS paradigm produces behavioural effects similar to those observed when using a paradigm in which task choice is explicitly indicated (Millington et al., 2013). Nevertheless, we cannot exclude the possibility of intention disruption, and moreover, we cannot specify the trials in which this might have happened. Further research is needed to investigate if and how these two methodological points might have affected the observations reported in the current study.

## Conclusions and outlook

Collectively, the present study provides empirical evidence for age differentiation at both the level of global task intentions and the level of the implementation of task intentions into the corresponding actions in voluntary task switching. This age differentiations is in line with the idea that different aspects of cognitive control processes are affected by age at a different pace, suggesting that while some cognitive control mechanisms that allow for multitasking are changing in adolescence but are stable across adulthood (task intentions), other mechanisms keep on changing throughout emerging adulthood (intention implementation).

Considering a broader perspective on multitasking, we conjecture that the performance costs we report here emerge as a result of a dynamic interplay between top–down and bottom–up influences on information processing, which together allow for flexible behaviour observed in voluntary task-switching situations. Accordingly, we suggest that these performance costs reflect limited cognitive resources, with their efficiency being age dependent and distinctively so for the two levels of cognitive control processes we investigated here.

**Acknowledgements** We thank Vincent Hoofs and Vera van 't Hoff for their tremendous help with data collection. Further, we thank Lea Ueberholz for her help with figures and tables and Lisa Hüther for proofreading the manuscript. Edita Poljac and Andrea Kiesel were supported by a Grant awarded to Andrea Kiesel within the Priority Program, SPP 1772 from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), Grant No. Ki1388-/7-1. Rianne Haartsen was supported by a grant from the European Community's Horizon 2020 Program under Grant Agreement No. 642996 (BRAINVIEW). Ervin Poljac was supported by the Marie Skłodowska-Curie mobility programme of the EU FP7 (REA Grant Agreement No. 624080).

**Compliance with ethical standards**

**Conflict of interest** The authors declare to have no conflict of interest. We agree to allow the journal to review the (raw) data if requested.

**Ethical approval** All procedures performed in the present study involve human participants and were in accordance with the ethical standards of the institutional, national research committee, and with the 1964 Helsinki declaration and its later amendments or comparable ethical standard.

**Informed consent** Informed consent was obtained from all individual participants (and both their parents for the minors) included in the study.

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