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Constraints on motor planning across the lifespan: Physical, cognitive and motor factors

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Abstract

Skilled adult movers plan for a comfortable end position even when this requires an uncomfortable start position (end-state-comfort effect). This ability declines in late adulthood and has been linked to age-related differences in cognitive functioning. Other factors, which may also drive difference in motor planning in later adulthood have not been systematically examined. These include perceptions of comfort and levels of motor imagery ability (one's ability to mentally simulate action / predict the outcome of action). Therefore, this study investigated the constraints on movement planning across the lifespan, including executive functions, general motor ability, physical constraints to movement and motor imagery ability. One hundred and twenty-two participants aged 20-81 years completed an end-state-comfort task with increasing levels of complexity. Individuals' executive functions, motor control, motor imagery ability and perceived rotation span were also examined. Age-related decline was shown in planning for sequential movements but not in simple single-step movements. Motor planning demonstrated an age-related difference which was associated with an increasing number of constraints as age increased, and in older adults chronological age influenced the effect of each constraint on motor planning. Age-related difference in motor planning may reflect effective compensatory strategies in response to differing constraints in motor imagery ability, executive functions, perceived rotation span and general speed and accuracy of movement as we age.

Keywords: End-State-Comfort, Executive Function, Motor Imagery, Motor Skill, Lifespan Development

Constraints on motor planning across the lifespan: Physical, cognitive and motor factors

When accomplishing everyday activities, we plan our actions in advance to not only optimise motor performance, but also minimise fatigue, maximise comfort and prepare for subsequent actions (Haggard, 1998; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992). One important indicator of successful movement planning is one's propensity to show the end-state-comfort (ESC) effect, whereby an individual starts a movement in an uncomfortable position if it means finishing in a comfortable or easily controlled end position (Rosenbaum et al., 1990; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012; Wilmut & Byrne, 2014b). For example, when reaching for an upturned glass with the intention of turning it over, skilled adults tend to rotate their wrist to grasp into a thumb down uncomfortable start position which results in a comfortable end position. This anticipatory effect reflects movement planning as one needs to consider the complete action of 'rotating the glass' in order to select the most appropriate initial grasp. The ESC task, therefore, examines one's ability to understand and plan for the consequences of an action.

Skilled young adults show a strong propensity towards ESC across a range of object manipulation tasks (Rosenbaum et al., 2012; Wilmut & Byrne, 2014b, 2014a). This ability to plan for ESC, although present at an early age (Stöckel & Hughes, 2016; Weigelt & Schack, 2010), has been shown to develop into late childhood (Wilmut & Byrne, 2014b). Recent studies demonstrate a growing interest surrounding the development of motor planning at the other end of the lifespan (Niermeyer, Suchy, & Ziemnik, 2017; Scharoun, Gonzalez, Roy, & Bryden, 2016, 2017; Stöckel, Wunsch, & Hughes, 2017; Wunsch, Weigelt, & Stöckel, 2017) and have highlighted a negative developmental trend for ESC planning in late adulthood (Scharoun et al., 2016, 2017; Stöckel et al., 2017; Wunsch et al., 2017).

In particular, age-related differences seem to be more conspicuous when task conditions are sufficiently complex or demanding. For example, Scharoun et al. (2016) and Scharoun et al. (2017) adopted the upturned glass paradigm and examined the number of grasps for ESC in different conditions: pantomime condition without any object or stimulus present, pantomime with an image or an object as a visual guide and actual grasping. In these studies, differences in ESC grasps between older (64-76 years) and young adults (22-25 years) only occurred in pantomime conditions where no stimulus or a visual guide was provided. However, in conditions where an actual grasping of an upturned glass was allowed, older adults' grasp selection for ESC did not differ from young adults. In another thread of research, Stöckel et al. (2017) and Wunsch et al. (2017) used a bar transport task, which mimics the upturned glass analogy, and considered both a unimanual and a bimanual condition. The number of grasps resulting in ESC was significantly lower in an older-old group (71-86 years) compared to young adults (19-28 years) and a younger-old group (60-70 years), particularly when the task was more demanding and bimanual movements were required. These findings have been discussed in light of cognitive function – with difficulties in planning for pantomime and bimanual movements being attributed to the increased cognitive demand of the tasks (Scharoun et al., 2016, 2017; Stöckel et al., 2017; Wunsch et al., 2017).

The constraints-based approach states that any motor response is constrained by the environment, the task and the individual (Keogh & Sugden, 1985; Newell, 1986). As such, any difference in motor behavior in older adults could be a result of environmental constraints, task constraints and/or individual constraints. Therefore, observed differences in executive function, which relate to the differences in motor control, could be such a constraint on movement. Indeed, higher-order cognitive skills have been argued to impose constraints in motor planning in ESC tasks (Logan & Fischman, 2011; Rosenbaum et al., 2012; Weigelt, Rosenbaum, Huelshorst, & Schack, 2009; Wunsch, Henning, Aschersleben, &

Weigelt, 2013). With evidence of a specific relationship between performance on an ESC task and executive function planning/problem solving, inhibition and working memory performance in children (Stöckel & Hughes, 2016). Stöckel et al. (2017) examined the relationship between ESC planning and cognitive functions in adults and found that one's propensity to show the ESC effect for the bimanual bar transport is associated with cognitive planning. When considering age-dependent associations, in addition to cognitive planning, fine motor dexterity and perceived grasp comfort were significantly associated with older adults' planning for ESC (Stöckel et al., 2017). It is therefore suggested that, in addition to decreased cognitive capabilities, the difference in motor planning with age may also, in part, be explained by physical factors, such as the reduction in the range of motion in the wrist experienced during aging (Rosenbaum, 2017). The limited movement may mean that older adults are either unable to adopt some start postures or that these are more uncomfortable affecting end-state positioning. This limited movement could also place a physical constraint on motor planning, thus changing the emerging movement. Indeed, in Stöckel et al.'s (2017) study, in addition to motor dexterity and response planning, perceived comfort was also associated with ESC planning in older adults. So, is it possible that older adults planned for ESC as much as young adults did, and the difference in task performance was partly due to the difference in the way in which grasp comfort was perceived? This gap in knowledge clouds our understanding of the likely difference of ESC effects with aging – will older adults still show a difference in planning for ESC once the range of motion and perceived comfort have been accounted for?

Another important aspect for consideration is one's ability to represent movement at an internal level. It is thought that a copy of the impending motor command, the efference copy, is used to predict the kinematic and sensory consequences of an action prior to any overt movement (Desmurget & Grafton, 2000; Wolpert, Diedrichsen, & Flanagan, 2011).

Within the context of ESC tasks, such a mechanism would allow a mover to predict the positioning of his/her hand at the end of a given movement and therefore select a start grip for end comfort. Previous studies have used motor imagery tasks to measure an individual's ability to simulate an action without any overt movement (Decety, 1996). Indeed, numerous studies have observed activation of similar neural networks during motor imagery tasks and during motor execution tasks using the same motor actions (Jeannerod, 2001). Furthermore research has demonstrated a clear association between motor imagery and motor planning in young adults (Wilmut, Hyde, Fuelscher, & Williams, 2012) and children (Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016).

It is known that such mental simulation of movements can be elicited both implicitly and explicitly. Implicit motor imagery refers to movement simulation which occurs as a consequence of a task, this is often examined using mental rotation tasks (Parsons, 1994). Explicit motor imagery refers to a movement simulation that occurs as a consequence of direct instruction of a task, this often examined using mental chronometry tasks (Decety, 1996). Research has shown that both implicit and explicit motor imagery declined as we age (Saimpont, Malouin, Tousignant, & Jackson, 2013). Implicit motor imagery is often considered using the hand laterality task, in which participants make judgements about the laterality of hand stimuli presented at varying angles in different postural orientations. It is believed that, in order to judge the laterality of a given hand image, one needs to mentally rotate an internal representation of their own hand to match the hand image being presented, which implicitly elicits motor imagery (Kosslyn, Digirolamo, Thompson, & Alpert, 1998). It was found that older adults (circa 65 years) tended to be slower (De Simone, Tomasino, Marusic, Eleopra, & Rumiati, 2013; Devlin & Wilson, 2010; Saimpont, Pozzo, & Papaxanthis, 2009) and less accurate (De Simone et al., 2013; Saimpont et al., 2009) than their younger counterparts (circa 20 years). Studies examining explicit motor imagery have typically used mental chronometry tasks where a given action is performed overtly and then also covertly and the temporal congruency between movement time and perceived movement time provides a measure of motor imagery, such studies are described below.

Research findings lead to the suggestions that explicit motor imagery performance in elders depends on the task difficulty and familiarity. For example, studies have found a comparable level of temporal congruency between executed and imagined movements in young and older adults during a variety of simple movements, including pointing, walking and sit-stand-sit (Saimpont et al., 2013), sequential finger movements (Caçola, Roberson, & Gabbard, 2013), finger opposition task, pronosupination of the forearm and making a fist (Zapparoli et al., 2013) and an arm raise with versus without an additional load (Personnier, Paizis, Ballay, & Papaxanthis, 2008). However, temporal incongruency in older adults was seen when the task was more demanding. For example, Skoura, Personnier, Vinter, Pozzo, & Papaxanthis (2008) and Skoura, Papaxanthis, Vinter and Pozzo (2005) found that, in contrast to young adults, older adults' overt movements adhered to Fitts Law (Fitts, 1954) when pointing between targets but their imagined/covert movements did not. Personnier, Kubicki, Laroche and Papaxanthis (2010) and Paizis, Skoura, Personnier and Papaxanthis (2014) found that, when pointing between three targets with an imposed level of accuracy, the movement times of imagined and actual movements of older adults lacked congruency, while this was not the case in young adults' movements. Finally, actual movements, but not imagined movements, were found to be longer in older adults compared to their young counterparts when pointing while adopting different stance positions which would have made balance more difficult (Mitra, Doherty, Boulton, & Maylor, 2016). From these studies, it would seem that in later adulthood motor imagery temporally mirrors executed action in simple tasks but that an apparent 'deficit' in motor imagery emerges when task complexity increases. Such an age-related decline in motor imagery may explain the role of age in the reduction of movements ending in comfort for more complex and demanding movements.

Given the constraints described above, the first aim of the current study was to determine the exact nature of age-related differences in motor planning, as measured by the propensity to end movements in comfort. In order to ensure a suitable level of task complexity, planning for ESC was examined during one-, two- and three-movement sequences. Based on previous studies our direct hypotheses (H1) was that the propensity to end in comfort will decrease as age increases but that this may only be apparent for the more complex tasks. The second aim of the current study was to describe the age-related differences in physical constraints to movement and in motor imagery ability. As described above the exact nature of the age-related differences in these areas remains unclear. Based on previous studies, our direct hypothesis (H2) was that we expect to see age-related differences in both motor imagery and the extent of physical movement, however, it is not clear at exactly what age the differences will first be identified. The final aim of this study was to determine the relationship between each constraint (executive function, motor ability, motor imagery and physical factors), age and motor planning. Based on previous studies, our direct hypothesis (H3) was that the primary factors involved in determining end-state-comfort would come from all of the constraint measures in the current study (i.e., executive function, motor ability and motor imagery) but that these would be mediated by age.

Method

Participants

A total of 122 participants ranging from 20 to 81 years old from Oxford Brookes University and the surrounding area took part in the study[1]. This study was reviewed and ethical approval granted by the University Research Ethics Committee at Oxford Brookes

University. Informed consent was obtained from all participants prior to taking part in the study. The participants were grouped into six age groups (i.e., 20-29, 30-39, 40-49, 50-59, 60-69 and 70-81[2] years). All participants reported to have normal or correct-to-normal vision and to be free from known movement difficulties related to any neurological deficit or comorbid condition. Participant information is given in Table 1.

Table 1 Details of the six different age groups

	20-29 years	30-39 years	40-49 years	50-59 years	60-69 years	70-81 years
N	21	20	21	20	20	20
Mean age	25.14	35.30	44.14	54.75	64.10	74.25
(SD)	(2.95)	(2.77)	(3.28)	(3.35)	(2.83)	(3.68)
Gender ratio (M: F)	10:11	10:10	11:10	10:10	10:10	10:10
Handedness (L: R)	1:20	1:19	2:19	2:18	1:19	4:16

Note: There was no significant age difference between female and male participants in each age group (all *t*s<1.41, *p*s>.18).

Tasks and procedure

Motor planning for ESC. Individuals' ability to plan for ESC was assessed using a grasp selection task that has been used in previous studies (Fuelscher et al., 2016; Wilmut & Byrne, 2014b, 2014a). As illustrated in Figure 1, participants were seated in front of a wooden octagon mounted on a backboard. The octagon was surrounded by eight different colors and could be rotated about its centre, so that an arrow, which initially pointed directly upwards, could be turned to point to one of the eight colors on the board. The size of the octagon varied according to the size of the participant's hand, with the diameters being 10.5 cm, 12.5 cm, and 13 cm. A start node was placed approximately one-third of the participant's arm length away from the octagon. Participants were instructed to grasp the start node between their thumb and index finger prior to the start of each trial and then to grasp the octagon and rotate it (in a clockwise or anti-clockwise direction) to make the arrow point to a sequence of one-, two- or three-colors in the order they were given. All movements were made using the preferred hand and recorded with a video camera. Participants were explicitly instructed that they should think about the way in which they grasped the octagon to ensure that they could complete the movement, as they would not be able to alter the hand grasp during each color sequence. However, the issue of 'comfort' was not mentioned. The task consisted of 36 movements, 12 for each sequence length. Color sequences were presented in a blocked fashion – the shortest movements first and moving up through the sequence lengths (Wilmut & Byrne, 2014b, 2014a).

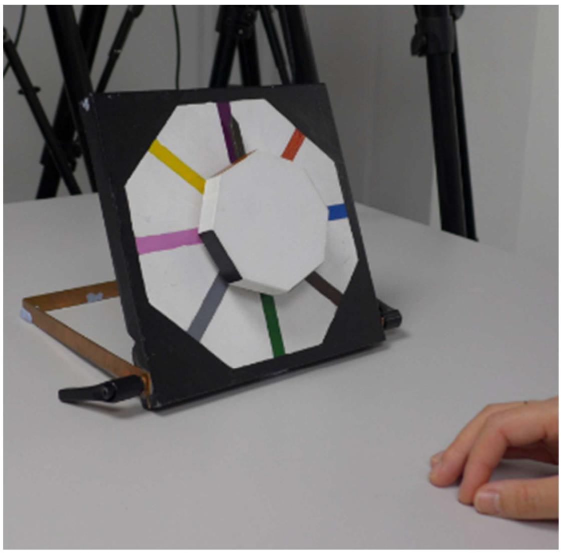

Figure 1: A photographic illustration of the set-up including the octagon to be grasped and the back board.

Following the motor planning task, in a separate session of **judgements of comfort**, each participant was asked to rate the level of comfort for each possible hand-grasp position on the octagon. The ratings were given on a 6-point scale: 1-very comfortable, 2-slightly comfortable, 3-neither comfortable nor uncomfortable, 4-slightly uncomfortable, 5-very uncomfortable and 6-impossible. A total of 16 comfort ratings were given by each participant (i.e., eight sides on the octagon with two possible hand-rotation directions – clockwise and anti-clockwise). These ratings were used for two purposes: 1. to determine individual physical constraints and 2. to determine the ESC level of movements in the motor planning task.

To consider individual physical constraints, we considered two measures: range of motion which was the frequency of uncomfortable responses (rating of 4, 5 or 6) in judgements of comfort, and perceived rotation span which was the total perceived possible rotation span of the hand calculated from the furthest medial rotation (receiving a rating less than 6) to the furthest lateral rotation (receiving a rating less than 6). A larger value suggests a greater perceived rotation span. In order to determine ESC level in the motor planning task, the end position of each one-, two- and three-movement was allocated the comfort rating that each individual participant subsequently rated that position[3], thus providing an ESC rating for each movement which ranged from 1 to 6 with a lower value indicating a more comfortable end position. Percentage of movements ending in ESC (ESC%) was then taken as the percentage of movements ending with a comfort rating of 1 or 2 (i.e., ending in a comfortable position).

Executive functions and motor ability. Executive functions were assessed using computer-based tasks. For all tasks, participants were seated at a comfortable distance from a laptop computer with a 13-inch screen. Executive function planning was measured using the Tower of London task (ToL; Phillips, Wynn, Gilhooly, Della Sala, & Logie, 1999). The Psychology Experiment Building Language (PEBL) computerized version was administered (Mueller & Piper, 2014) using set A of Phillips et al. (1999) that consisted of eight 5-disc trials. Participants were asked to re-arrange a pile of discs, in as few steps as possible, from their original configurations to the configuration shown at the top of the screen while moving only one disc at a time and not moving a disc onto a pile that had ‘no more room’. In line with previous research (Stöckel & Hughes, 2016; Stöckel, Wunsch, & Hughes, 2017), two measures were considered: 1.ToL%, percent of trials completed using the minimum number of moves; 2. ToLtime, the total time used to solve each problem/trial.

Executive function of inhibition was measured using a size-value interference task (Henik & Tzelgov, 1982; Tzelgov, Meyer, & Henik, 1992), which was controlled and administered using PsychoPy (Peirce, 2007). The task consisted of two conditions, comparison of the numeric value and comparison of the physical size. In both conditions, participants were presented with a series of digit pairs with each pair consisting one smaller digit (1, 2, 3 or 4) and one larger digit (6, 7, 8 or 9). In each pair, the digits also varied in physical size, with one being printed in a larger size and the other one in a smaller size (height ratio 3:2). Therefore, the stimuli could be: congruent stimuli, where numerically larger digits were physically larger; incongruent stimuli, where the numerically larger digits were physically smaller; and neutral stimuli, where the same digits were printed in different sizes, or different digits printed in the same size. Both the physical and numeric task included eight congruent, eight incongruent stimuli and 16 neutral stimuli. Participants were asked to respond to the larger digit in either numeric value or physical size by pressing the corresponding keys labelled on the keyboard. Each trial started with a central fixation cross for 500 ms, followed 200 ms later by a pair of digits. The digit pair remained on the screen until a response was given by pressing a designated key or 10 s had elapsed. An interval of 500 ms was scheduled after each trial. For each trial, we recorded response times (RT) to the nearest 1 ms and response accuracy. The measures of executive inhibition were computed as differences in average response time and error rates between incongruent and neutral conditions for both numeric value and physical size comparisons. In line with Salthouse (2010), reaction times and accuracy were combined using z-scores yielding a single value for the numeric value comparison (NumZscore) and a single measure for the physical size comparison (PhyZscore). Higher values in these measures indicate greater difficulties in the inhibitory control of responding to the irrelevant information.

Working memory capacity was measured with the Corsi-block tapping test (Corsi, 1973), which was administered using the PEBL (Mueller & Piper, 2014). Participants were shown an array of randomly placed blue blocks on a black background, and a subset of these blocks changed color (i.e., from blue to yellow) in a sequential manner. The participants were asked to click on the blocks in the order in which they changed color. The number of blocks in a sequence was increased from 2 to 9 with two trials per sequence length. If at least one of these trials was responded to correctly, the sequence length was increased in subsequent trials, if neither trial was responded to correctly, the test was terminated. The memory span was used as the outcome measure and computed as the sum of start length (i.e., 2) and the total number of correct trials divided by the number of trials per length (i.e., 2).

Individuals' general motor ability was assessed using the short version of the Bruininks Motor Ability Test (BMAT-short; Bruininks & Bruininks, 2012). A raw total score was calculated for each participant and then standardized using age appropriate bands. As there are no standardized scores from the age range 20-39 years, the lowest age band was used for these participants. This standardized BMAT score was used as the measure of motor ability.

Motor imagery: Two tasks were used to measure implicit and explicit motor imagery respectively, the hand laterality task and a mental chronometry task. In the hand laterality task, participants were seated at a comfortable distance from a 13-inch laptop screen which displayed images of single 'disembodied' hands. Their task was to decide whether the image was a left or a right hand as quickly and as accurately as possible. The hand images were presented at eight rotation angles ranging from 0° to 315° with 45° increments (i.e., 0°/360°, 45°, 90°, 135°, 180°, 225°, 270° and 315° clockwise for both hands). All stimuli were shown in either palm view (palm of the hand facing participants) or back view (back of the hand facing participants). Participants completed five practice trials with feedback followed by 80 test trials with each hand stimulus at 0° and 180° appearing four times and other angles twice. The hand stimuli were presented in a random order using PsychoPy v1.8 (Peirce, 2007) and remained on screen until a response was given by pressing a pre-specified key on the keyboard or 10 s had elapsed. Inter-trial interval was set at 500 ms. For each trial, response time (RT) to the nearest 1 ms and response accuracy were recorded. Participants were instructed to rest their index fingers on the pre-specified keys, of a standard keyboard, and not to move their hands during the task. However, the issue of 'motor imagery' or 'implicit movement' was not mentioned.

Prior to analysis, data were screened to remove anticipatory (responses under 250 ms) or significantly delayed (over 3.0 SDs) responses. This resulted in over 95.2% valid trials for all age groups. Mean accuracy was calculated as the proportion of correct responses over these valid trials and mean response time (RT) was calculated using correct trials only (De Simone et al., 2013; Devlin & Wilson, 2010; Saimpont et al., 2009) and was normalized using the RT for 0^{o}. Mean RTcorrected and accuracy for angular rotations of 0° (not included for RTcorrected), 45°, 90°, 135° and 180° were calculated by combining back and palm views and collapsing medial and lateral rotations. In addition, an overall measure of accuracy (HLTAccuracy) and RT corrected (HLTRTcorrected) were also calculated. As RTcorrected showed a linear relationship, the slope of the linear function between this and rotation angles was extracted for each participant giving HLTSlope for each participant.

In the mental chronometry task, participants were asked to write (executed movement) and imagine writing (imagined movement) the letters of the alphabet from a to z in the lower case using the preferred and then the non-preferred hand. Participants were comfortably seated on a chair in front of a table with a sheet of paper and a pencil on the table. In the executed writing condition, participants were instructed to write the alphabet letters in a natural way at a comfortable speed with their eyes open. In the imagined writing condition, participants were asked to imagine writing while holding the pencil with eyes closed. Participants were explicitly instructed to *imagine* themselves kinaesthetically performing the writing movements while not executing any movement as if writing. This is similar to instructions given previously using the same task (Oikawa, Hirano, Taniguchi, & Maruyama, 2016). The times of executed and imagined writing were recorded by the participants. In all conditions, the participant started a stopwatch, held in the hand they were not using, started it just before they had started writing/imagining and stopped it once they had finished. This self-timing methodology has previously been validated for both young and older participants (Courtine, Papaxanthis, Gentili, & Pozzo, 2004; Papaxanthis, Pozzo, & Schieppati, 2003; Personnier et al., 2008; Sirigu et al., 1996). Prior to the start of each condition (preferred hand imagined, preferred hand executed, non-preferred hand imagined, non-preferred hand executed), participants practised the task using just the first ten letters of the alphabet. After practice, each participant completed two imagined trials followed by two executed trials of each hand. This fixed order was used to prevent participants from knowing the time taken by executed writing from reading the stopwatch and then estimating the imagined writing time. The mean duration of each hand in each writing condition was calculated for each participant. The absolute difference between the executed and imagined movements was calculated with a score of zero indicating perfect accuracy, and this gave Chronometry Preferred and Chronometry Nonpreferred measures.

Statistical analysis

To address the first and second aim (1. the nature of age-related differences in motor planning and 2. the nature of age-related differences in motor imagery and in physical constraints) we considered how performance in the motor imagery tasks, perceived rotation span and motor planning differed across the age groups using ANOVA. For the ESC task, an additional factor of sequence length was included and both ESC rating and ESC% were used as measures of motor planning. For factors where sphericity could not be assumed, *F*-ratios with adjusted degrees of freedom (using the Greenhouse-Geisser correction) and *p*-values are reported. And in order to reduce the chance of Type I error, Sidak correction was used following multiple testing. In order to address the third aim (factors of executive function, motor imagery, physical and motor ability which constrain motor planning at different age points) stepwise regression analyses were run using ESCRating and ESC% as outcome variables. Predictors initially included were: the constraints variables (ToL%, ToLtime, NumZscore, PhyZscore and Memory span, HLTAccuracy, HLTSlope, Chronometry Preferred and Chronometry Nonpreferred and perceived rotation span), chronological age and interactions between chronological age and each constraint were added. To create interaction terms variables were centered to minimise multicollineraity. Multicollinearity of the predictors in each model was examined for both ESC rating and ESC%, in both cases the correlation between HLTslope and HLTRTcorrected was high (coefficient over .40), for this reason HLTRTcorrected was not entered into the mixed linear model. The variables entered had a suitable level of collinearity with the VIF factor less than 2.77 for all variables. For all statistical testing, the alpha level was set at 0.05.

Prior to conducting statistical analyses, all data were checked for outliers; in order to ensure cases were not removed in error, a conservative cut-off of z-scores falling three standard deviations above or below the mean was adopted. Four participants were excluded due to outlying scores in the executive function tasks (this included 3 participants from the 40-49 group and 1 participant from the 60-69 age group). These participants were excluded from all analyses which used these measures. In addition, two further participants (one from the 30s and one from the 40s group) were excluded due to outlying scores in the motor imagery tasks, and these participants were excluded from all analyses which used these measures.

Results

ESC planning across the lifespan

Both the percentage of movements ending in ESC (ESC%) and the overall rating of comfort of the end position (ESC rating) were considered. A two-way ANOVA revealed a significant effect of sequence (ESC rating: $F(2, 232) = 187.79$, $p < .001$, $\eta_p^2 = .62$; ESC%: $F(2, 232) = 185.91$, $p < .001$, $\eta_p^2 = .62$). One-movement sequences were rated as more comfortable (lower rating value) and ended more often in a comfortable position (higher ESC%) than two- or three-movement sequences (all ps < .001), and two-movement than three-movement sequences (both ps < .05).

While the main effect of age group was not significant for either measure, ESC rating: $F(5, 116) = 1.84$, $p = .11$; ESC%: $F(5, 116) = 1.62$, $p = .16$, a significant two-way interaction between age group and sequence length was found for ESC rating, $F(10, 232) = 2.88$, $p = .002$, $\eta_p^2 = .11$ and ESC%, $F(10, 232) = 2.28$, $p = .015$, $\eta_p^2 = .09$ (Figure 2). This interaction was explored using simple main effects analysis and post-hoc comparisons. A significant main effect of sequence length was found for each age group: for ESC rating, all Fs > 17.84, ps < .001; for ESC%, all Fs > 17.81, ps < .001. For all the age groups, a lower rating value (more comfortable) and higher ESC% was found for one-movement sequences compared to two- and three-movement sequences (all ps < .001). However, a significant difference between two- and three-movement sequences was found for the 70+ group only, where two-movement sequences ended more comfortably than three-movement sequences (lower rating and higher ESC%, both *p*s < .001).

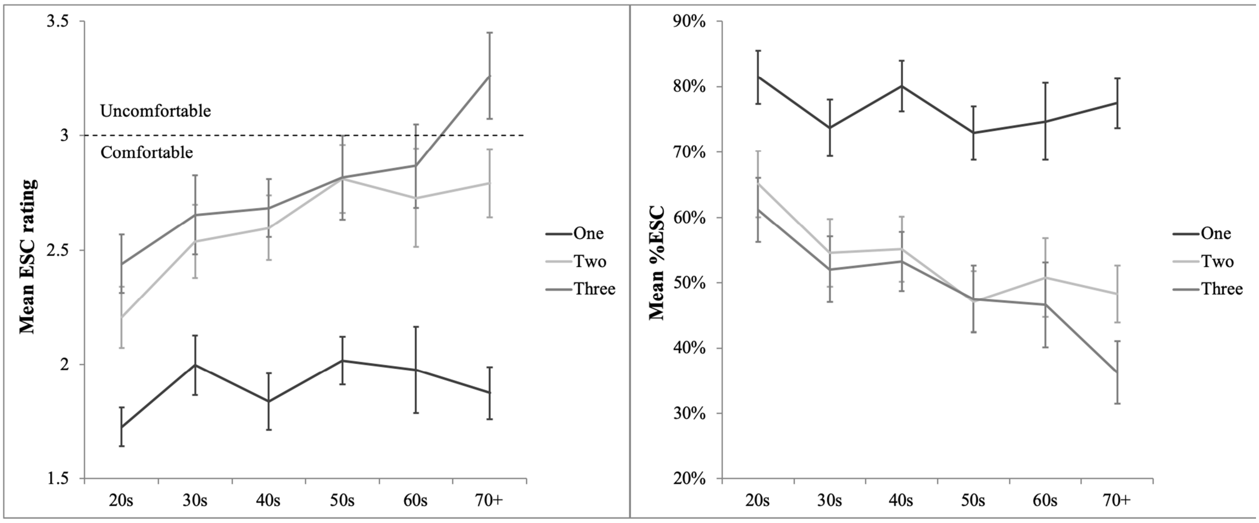

Figure 2. ESC rating and ESC% for each sequence length across all the age groups (error bars represent standard error). Rating below the reference line at 3 were considered comfortable and above uncomfortable.

Physical constraints across the adult lifespan

Chi-square test was used to examine age-related differences in the range of motion variable, i.e., whether 'uncomfortable' responses become more frequent as age increases. No significant association between age group and the frequency of comfortable/uncomfortable responses was found, $X^2(5) = 5.68$, $p = .34$. In addition, we examined the effect of age group on the perceived rotation span using a one-way ANOVA. The main effect of age group was significant, $F(5, 116) = 4.48$, $p = .001$, $\eta_p^2 = .17$, with a lowered perceived rotation span in the 60-69 and 70-81 group compared to the 20-29 group. See Table 2 for the perceived rotation span.

Table 2. Mean values (SD) of the perceived rotation span in degree.

	20s	30s	40s	50s	60s	70+
Perceived rotation span (degree)	469 (56)	443 (60)	431 (50)	439 (54)	412 (60)	392 (58)

Motor imagery across the adult lifespan

Hand Laterality task

HLTAccuracy – A significant main effect of rotation angle was found, $F(4, 460) = 73.54$, $p < .001$, $\eta_p^2 = .39$, where a significant drop in accuracy was found between each angle of rotation after 45° (0° = 45° > 90° > 135° > 180°, all *p*s<.001). The interaction between age group and rotation angle was also significant, $F(20, 460) = 2.14$, $p = .029$, $\eta_p^2 = .09$. Simple main effects tests demonstrated a significant effect of rotation angle for each age group, all *F*s > 2.61, *p*s < .039. For the 20-29 and 30-39 group, a significant drop in accuracy was found for rotation of 180° (0° = 45° = 90° = 135° > 180°, all *p*s<.001). For the 40-49, 50-59 and 60-69 group a drop in accuracy was seen after 90° (0° = 45° = 90° > 135° = 180°, all *p*s<.001). Finally, for the 70-81 years a drop in accuracy was seen after 45° and then again for each 45° increase (0° = 45° > 90° >135° > 180°, all *p*s<.001). The main effect of age group was not significant. See Figure 3 for an illustration of these data.

HLTRTcorrected – The main effect of age group was significant, $F(5, 115) = 3.59$, $p = .005$, $\eta_p^2 = .14$, with the 30-39 year group being significantly faster than the 70-81 year group ($p < .05$). The analysis also revealed a significant main effect of rotation angle, $F(3, 345) = 210.97$, $p < .001$, $\eta_p^2 = .65$, where a significant reduction in response time was seen with each reduction in rotation angles, all *p*s < .001. The two-way interaction was also significant, $F(15, 345) = 2.46$, $p = .004$, $\eta_p^2 = .10$. To further examine age-related differences in the ability to rotate images using implicit motor imagery, a regression coefficient analysis was conducted between angle of rotation and HLTRTcorrected. The slope data were then entered into a univariate ANOVA to examine the differences between age groups. A significant effect was found, $F(5, 121) = 4.40$, $p = .001$, $\eta_p^2 = .16$, where 70-81 years group had a significantly steeper slope, hence being less efficient, compared to 20-29, 30-39 and 40-49 years groups (all *p*s < .05). See Figure 4 for the slope data.

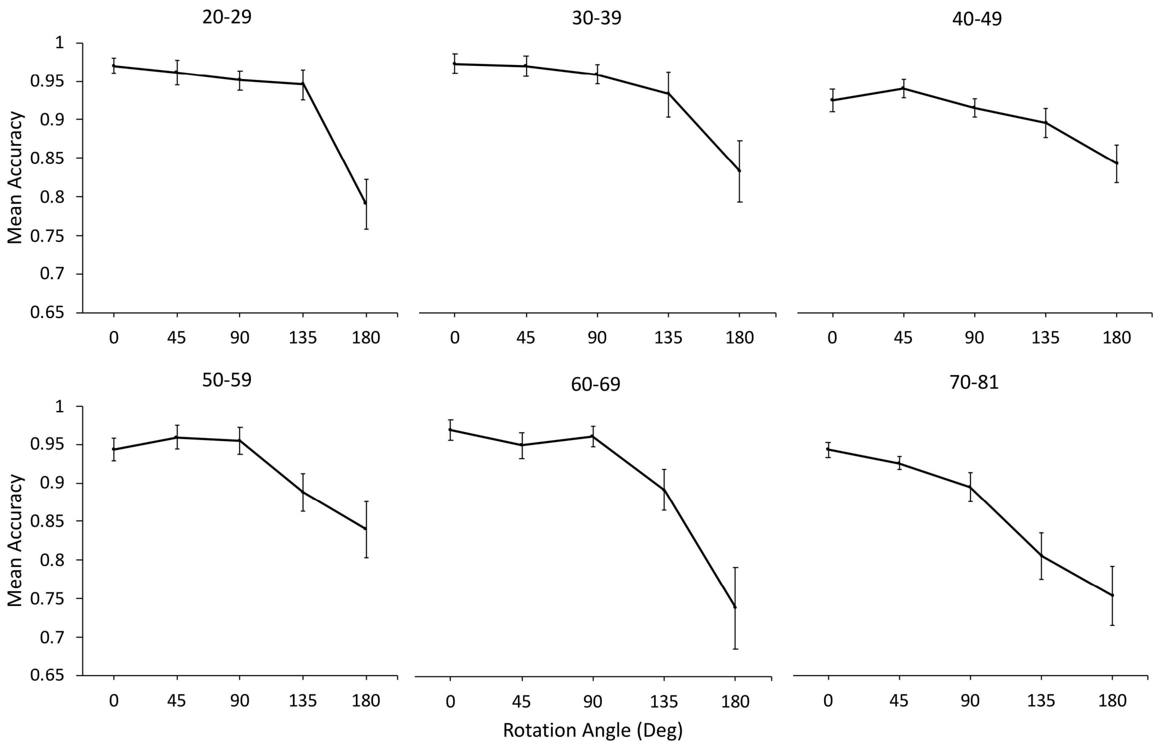

Figure 3: Accuracy data of the hand laterality task given for each age group, error bars represent standard error.

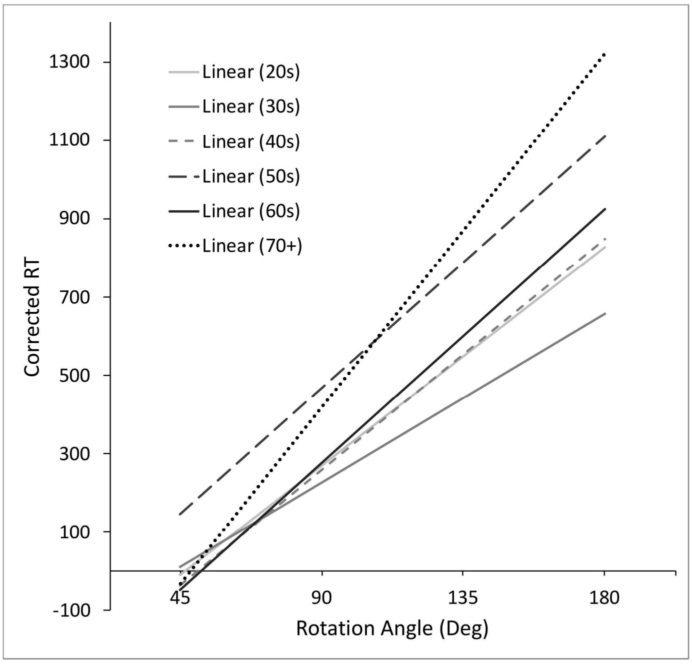

Figure 4. Fitted linear trend of mean RTCorrected for 45°–180° of each age group.

Mental chronometry task

The analysis of temporal accuracy (i.e., the absolute difference between executed and imagined movement times) revealed a significant main effect of hand, $F(1, 114) = 14.69$, $p < .001$, $\eta_p^2 = .12$, where the preferred hand demonstrated a lower value and hence a greater temporal accuracy compared to non-preferred hand. The main effect of age group was not significant nor was the interaction between age group and hand. See Figure 5 for an illustration of these data.

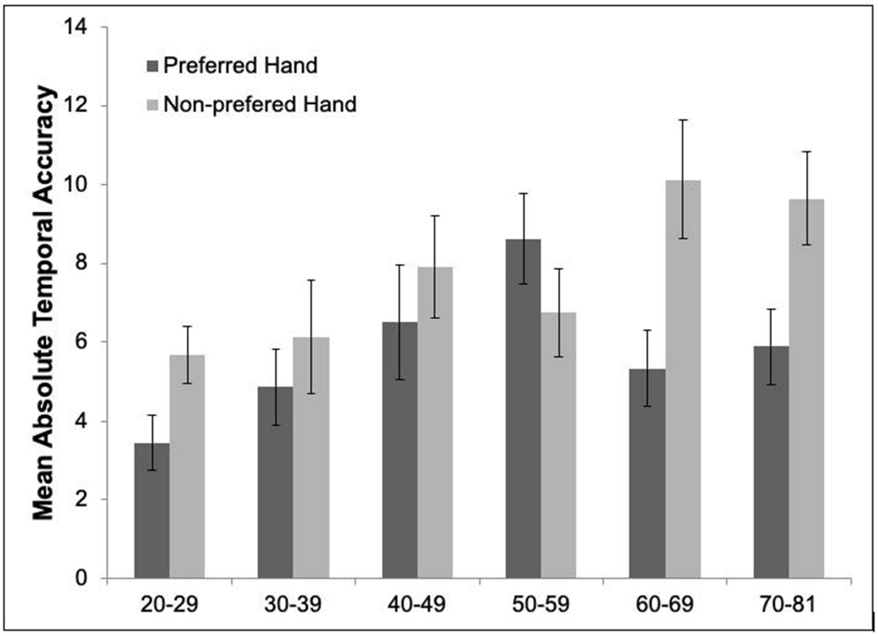

Figure 5. Mean absolute temporal accuracy for each age group and both the preferred and non-preferred hand.

Factors which constrain motor planning at different age points

Stepwise regression was used to investigate the effects of each constraint and the interaction between each constraint and chronological age on ESC rating and ESC%. This was conducted for both ESCRating and ESC% for one- two and three-sequence length. The pattern of significant and non-significant effects was the same for ESC Rating and ESC% and so the figures given here are for ESC Rating only. Findings are described below with coefficients estimates in Table 3.

For one-sequence movements, three significant models were described, the first with only perceived rotation span, the second with the addition of BMAT and the third with the addition of chronological age x PhyZscore. The relationships described show that as perceived rotation span and motor ability increase ESC rating decreases (end movements become more comfortable).

For two-sequence movements, four significant models were described, these included the predictors described above for one-sequence movements but also included a measure of motor imagery (HLTslope); as the steepness of the HLTslope increases (less efficient motor imagery), ESC rating increases (less comfortable end movements).

Finally, for three-sequence movements, the same variables were once again predictive with the addition of chronometry nonpreferred being predictive and the age x PhyZscore being replaced by age x memory span. As motor imagery ability, perceieved rotation span and motor ability increase ESC rating decreases (end movements become more comfortable).

Table 3. F change, R^2 change, *t*-values and *p*-values for the significant predictor variables. Provided for both ESC rating only. All references to age refer to chronological age and rotation refers to perceived rotation span

		***F* change**	***R^2* change**	***p***	**Variable**	**Beta**	***t***	***p***
One-sequence movements	Model 1	9.36	.08	.003	Rotation	-.003	-3.06	.003
	Model 2	7.25	.06	.008	Rotation	-.003	-3.13	.002
					BMAT	-.005	-2.69	.008
	Model 3	4.06	.03	.046	Rotation	-.003	.83	-.33
					BMAT	-.005	-2.33	.022
					Age x PhyZscore	-.011	2.02	.046
Two-sequence movements	Model 1	19.94	.149	<.001	Rotation span	-.005	-4.47	<.001
	Model 2	13.16	.089	<.001	Rotation span	-.005	-5.07	<.001
					HLTslope	.057	3.63	<.001
	Model 3	9.66	.061	.002	Rotation span	-.005	-5.22	<.001
					HLTslope	.053	3.51	.001

					BMAT	-.007	-3.11	.002
	Model 4	4.50	.027	.036	Rotation span	-.005	-5.40	<.001
					HLTslope	.055	3.66	<.001
					BMAT	-.006	-2.72	.008
					Age x PhyZscore	-.013	-2.12	.036
Three-sequence movements	Model 1	27.60	.20	<.001	Rotation span	-.006	-5.25	<.001
	Model 2	7.05	.05	.009	Rotation span	-.006	-5.36	<.001
					Age x Memory span	-.012	-2.66	.009
	Model 3	6.023	.04	.016	Rotation span	-.006	-5.71	<.001
					Age x Memory span	-.012	-2.72	.008
					HLTslope	.039	2.46	.016
	Model 4	6.42	.04	.013	Rotation span	-.006	-5.69	<.001
					Age x Memory span	-.012	-2.80	.006
					HLTslope	.040	2.56	.012
					Chronometry Nonpreferred	-.026	-2.53	.013

Discussion

The current study investigated adults' grasp selection for ESC during sequential movements across the lifespan. Firstly, we considered how motor planning, motor imagery, physical constraints differed across the lifespan, and then we considered which of the constraints significantly impacted on the planning for ESC.

Motor planning across the lifespan

Previous studies classified a movement as comfortable or not depending on whether the palm/thumb faces/points up or down. When studying age-related differences, however, individual differences in the perception of comfort are important. If young and older adults perceive the comfort of hand positions differently, a unified criterion of judgement of comfort for everyone may occlude or exaggerate age-related differences. Therefore, in this study, we took individuals' judgement of comfort into account when quantifying the comfort of grasps by using individuals' rating of each hand position. In this way, more tailored measures of ESC performance were yielded. Two ESC planning measures were calculated in this study: the percentage of movements ending in a comfortable position (ESC%) and the quantification of end state comfort (ESC rating). These data showed consistent results that an age-related difference was found in planning for ESC in sequential movements (e.g. three-movements in a sequence) even after accounting for individual differences in comfort. This is in line with previous studies focusing on the ESC planning in late adulthood that older adults showed more difficulties in planning for ESC compared to young adults (Scharoun et al., 2016, 2017; Stöckel et al., 2017; Wunsch et al., 2017). These findings suggest that this age-related difference in ESC performance was not, at least, entirely due to increased discomfort of grasps which occur alongside aging but reflected reduced ability in forward motor planning.

More specifically, this reduced ability to plan movements as age increases appeared to be more conspicuous when there were multiple movements in a sequence. In this study, we manipulated the level of difficulty systematically by increasing the length of the movement sequence. It is known that young adults can plan two- to three-steps ahead for ESC (Haggard, 1998; Wilmut & Byrne, 2014b, 2014a), which is also supported by data of this study that young adults successfully planned for ESC during one- (ESC% – 80%), two- and three-movement sequences (both ESC% over 60%). For older adults (60s and 70+), the ability to plan for ESC during single movements was well preserved along aging (ESC% – 70-80%); however, there was a tendency of reduced ability to plan for multiple movements in a sequence as age increases. In particular for individuals over 70, a marked difference was found in the planning for three-movement sequences, where only less than 40% of movements ended comfortably. This is even lower than bimanual movements (over 65%; Stöckel et al., 2017; Wunsch et al., 2017), which suggests a 'drop' or difference at 70 in the forward planning for sequential movements. To be clear, we are not necessarily advocating a deficit or decline in motor planning per se, but rather suggesting that motor planning (or the goals of motor planning) changes with age due to specific constraints on movement. That is, as we age, the associated advantages of ending a movement comfortably no longer outweighs the associated disadvantages of starting a movement uncomfortably.

The interaction between age and task complexity is consistent with previous studies where differences in ESC performance between older and young adults were only found significant in more complex task conditions, such as rotating a pantomime glass (Scharoun et al., 2016, 2017) or bar-transport using both hands (Stöckel et al., 2017; Wunsch et al., 2017). This is also true in children (Stöckel & Hughes, 2016). In less complex conditions, where an actual glass rotation was allowed or transporting a bar using one hand, older adults adjusted their movements for ESC as much as young adults did. It has been argued that this may be due to the high cognitive demand for complex conditions.

One possible explanation is that older adults may have adopted more adaptive strategies to achieve better compensation for age-related changes in motor planning. It is known that older adults tend to use compensation to maintain cognitive functions (Dockree, Brennan, O'Sullivan, Robertson, & O'Connell, 2015; Samu et al., 2017) and maximize well-being (Carpentieri, Elliott, Brett, & Deary, 2017). It is, therefore, possible that in the current study when similar motor planning performance was achieved across different age groups, very different strategies might have been adopted, and different amount of effort used to resolve the task. However, according to the compensation hypothesis, such activation is only effective when task demand is moderate or relatively low (Reuter-Lorenz & Cappell, 2008). For highly demanding tasks, when a resource ceiling is reached, the compensatory mechanism will be no longer effective. Our data support this hypothesis – when there were three-movements in a sequence, older adults' motor planning performance level dropped, especially in comparison to those of young adults, which suggests that planning for three-movement sequences might reach older adults' resource ceiling of compensation. However, this study was not designed to examine the compensatory mechanism in motor planning, so it is impossible to make conclusions in this regard. Future studies are needed to provide evidence of compensatory brain activity for motor planning in older adults, for example, by introducing response time limit to the task, age-related differences in planning performance may be revealed during simpler movements. It is also important to consider what strategies are adopted to compensate age-related declines to maintain function, as this may help build effective interventions.

Motor imagery across the lifespan

Our study also considered motor imagery across the lifespan. In terms of implicit tests of motor imagery, there was no obvious evidence that older adults were less accurate than young adults in the judgement of hand laterality, which is in line with previous findings that accuracy was comparable between a group of older adults and a group of young adults (Devlin & Wilson, 2010; Saimpont et al., 2009; Zapparoli et al., 2016). However, it is important to note that the lack of a difference in accuracy in all of these studies may be due to ceiling effects and if given a task which allowed a higher range of variability in the lower angles we may have seen absolute accuracy differences. One factor which may point towards this is the variation in the trend of judgement accuracy along hand rotation angles across age groups. In terms of the effect of rotation, we examined the response time and the slope of response time change along the rotation angle. In line with previous studies of this type (De Simone et al., 2013; Devlin & Wilson, 2010; Saimpont et al., 2009), our data showed slower responses (longer RT) with increased age and also a significantly steeper slope (i.e., a greater increase of RT with each increase of rotation angle) was found for 70+ years group compared to those below 50. Taking together accuracy and slope data, the implicit motor imagery performance did not show a substantial difference through adulthood and only became apparent at a later life with advanced age (70+).

In terms of explicit tests of motor imagery, when considering the size of temporal deviation of motor imagery, the imagined duration was closer to the executed duration of dominant hand compared to non-dominant hand. This temporal incongruency between imagined and executed non-dominant hand writing was exaggerated in the oldest group. While in terms of age-related effect, our data showed that explicit motor imagery of writing movements is not substantially modified in healthy aging. This is in line with findings from previous studies examining upper-limb movements (Personnier et al., 2008; Skoura et al., 2005, 2008), where movements were completed using a natural/comfortable speed of each individual without a time limit, the ability to mentally simulate movements seems to maintain along aging. However, when taking a closer look at the non-preferred hand, older adults (60-81 years) showed significantly lower temporal accuracy of imagined writing compared to young adults in their 20s and 30s. This seems due to the demanding nature of non-dominant hand writing, which is perceived as more difficult to imagine and requires more effort to complete (Decety & Lindgren, 1991). This resembles the task conditions that required fast moving speed and/or used smaller target size to increase difficulty and decrease familiarity in previous studies (Personnier et al., 2010, 2008; Skoura et al., 2005, 2008). Again, these findings suggest that the age-related dissimilarity of temporal characteristics between executed and imagined movements only becomes obvious when the required movements are particularly demanding and/or unfamiliar.

Which factors constrain motor planning?

We considered which of our measured constraints: physical factors, cognitive capability and motor imagery could influence motor planning performance. Our data showed that different factors constrained movement across the three different sequence lengths. Interestingly, in the current study we found that the perception of comfort was highly predictive in terms of motor planning in both groups; this demonstrates the importance of the perception of comfort in motor planning across the lifespan rather than only being a factor with advanced aging.

Furthermore, measures of motor imagery were predictive of motor planning in the two- and three- sequence movements, with a more efficient motor imagery process (shallower slope on the HLT task) resulting in a greater propensity to end movements in comfort. This is in line with research demonstrating associations between motor imagery capacity and movement control (Hyde, Wilmut, Fuelscher, & Williams, 2013; Sooley, Cressman, & Martini, 2018). According to the hypothesis of internal models, every movement we make has a corresponding mental representation and simulation which is used to predict the consequences of action prior to the execution of that action (Desmurget & Grafton, 2000; Wolpert et al., 2011). It is this internal model of imagined movements that allows us to determine where our hand will be at the end of a movement and thus where it needs to be at the start. It would seem that differences in the ability to perform efficiently on tests of motor imagery may influence one's ability to plan for comfort and that this effect is present irrespective of age (demonstrated by a lack of age x motor imagery task interaction).

This supports previous studies which have found a relationship between motor imagery and motor planning in young adults (i.e., Hyde et al. 2013) and extends the findings into older adulthood.

In addition, our data also showed significant associations between executive functions and motor planning for ESC. For one- and two-sequence movements this was demonstrated via a chronological age x ZPhyIn interaction. For three-sequence movements it was demonstrated by a chronological age x memory span interaction. These interactions demonstrate that chronological age mediates the relationship between the executive function in question and motor planning. In each case the executive function (inhibition for one- and two-sequence movements and memory span for three-sequence movement) had a lesser impact on motor planning in the younger compared to the older participants. This is consistent with previous research by (Stöckel et al., 2017), where individuals' cognitive proficiency was found to be associated with ESC planning for bar-transport and that this the association between cognitive proficiency and motor planning for ESC was mainly driven by the older adults (61-86 years), whereas in young adults (19-28 years) none of the cognitive ability measures was related to ESC planning. Our study further shows that this effect of executive function on motor planning is further influenced by chronological age. This seems to suggest increasing constraints on motor planning as we pass through the adulthood and into a later life – the age-related decline in executive functions may in turn have detrimental impacts on motor planning in older adults with advanced age. One important caveat to this is that the motor planning task used in the current study required a high level of visually guided planning and visually guided movement. We know from previous research that the reliance on vision to execute and update movement increases as we get older (for example see Coats & Wann, 2011). Therefore, the constraints on motor planning for tasks which do not so easily lend themselves to visually guided planning might be very different from those seen in the current study.

Our data has also revealed that individual motor planning ability for ESC was also influenced by the general motor ability (BMAT). With a better motor ability being associated with a greater number of movements ending in comfort and this relationship was irrespective of age.

A limitation of the current study is that we did not consider the effects of individuals' life experiences and practices they had that may affect their motor planning abilities. However, this study was not designed to answer this question; longitudinal studies are needed to explore individuals' lifespan development. Another aspect of development could be to consider an even wider age range. In this study, we found that motor planning ability declines slowly and differences only become apparent in the very old age group (over 70 years) during complex sequential movement planning. Therefore, it seems worthwhile to study older adults (over 80 years) or introduce tasks examining other aspects of motor planning that may involve not only hand movements but a broader range of movements, such as gross movements and coordination.

This is the first study which has investigated motor planning ability across the adult lifespan. In this study, over 120 participants ranging from 20-81 years took part with ages equally spread across this range, which allowed us to understand the differences in motor planning across the adult lifespan and how cognitive, motor and physical constraints can influence this. We found that the ability to plan for one sequence movements was well preserved along aging with some small fluctuations of the performance. In contrast, we saw a drop in planning for end-state-comfort for two- and three-sequence movements which only became apparent in the oldest age group over 70.

In summary, this study has demonstrated that individuals' motor planning ability and to some extent motor imagery ability differs as we age and in particular for more complex tasks. This age-related difference in complex sequential movements was associated with individuals executive planning, motor ability, motor imagery and perceived rotation span and out of these only executive function was mediated by age. These findings demonstrate an increasing number of factors which constrain movement as age increases and the constant influence of age. These differences in motor planning may reflect effective compensatory strategies in response to differing constraints in motor imagery ability, perceived comfort and general speed and accuracy of movement as we age.

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[1] G-Power (Faul, Erdfelder, Lang, & Buchner, 2007) calculated that 114 participants were needed given the study design and the expectation of a large effect size.

[2] The age range of this group was increased due to opportunistic sampling.

[3] To ensure the reliability of hand position coding, 10% of participants (one female and one male from each age group) were coded by a second coder. Inter-rater reliability analyses revealed excellent agreement (Cohen's kappa=0.99, $p<.001$).