The 'why' of reaching: second-order planning across the adult lifespan

Kate Wilmut and Shan Wang

Oxford Brookes University

Author note

Kate Wilmut, Psychology, Health and Public Development, Oxford Brookes University, Oxford, UK; Shan Wang, Psychology, Health and Public Development, Oxford Brookes University, Oxford, UK

Corresponding authors: Kate Wilmut, Faculty of Health and Life Sciences, Gipsy Lane, Oxford Brookes University, Oxford, OX3 0BP

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Abstract

Second-order planning, planning which takes into account imminent and subsequent task demands, has been shown to be essential during everyday movement. For example, the kinematics of a 'reach to an object' action have been shown to be linked to the intended goal for the object (the prior intention). However, it is unclear whether this type of second-order planning for prior intention is preserved during aging, or indeed how this differs across the adult lifespan. Kinematics of a reach action preceding four prior intentions, place in a 'tight' hole, place in a 'loose' hole, throw or lift were measured in 122 aged from 20-81 years. The kinematics of the reach movement demonstrated that all participants tailored their reach movement to the prior intention, with the deceleration period of the reach discriminating across groups. The 20s and 30s group showed a different deceleration period during the reach for tight versus loose place prior intentions, this was not seen after 39 years of age and the 70+ group showed no discrimination across the deceleration period for the four prior intentions. When considering movement efficiency of the place actions we found it could be predicted by age and that this relationship was mediated by discrimination across the deceleration period. This study demonstrates that a clear difference is seen in the way in which second-order planning is used across the lifespan and that this has implications for movement efficiency.

Keywords: prior intentions, kinematics, movement efficiency, motor control, aging

The ‘why’ of reaching: second-order pl anning across the adult lifespan

In order to interact with our environment we plan and execute many thousands of fast and accurate movements. In the majority of cases these movements are not executed in isolation but are instead executed as a sequence of actions, for example, reaching to pick up a pen, removing the lid, bringing the hand to the paper and starting to write. In a recent review, Rosenbaum, Chapman, Weigelt, Weiss and van der Wel (2012) referred to planning which takes into account both imminent task (i.e. picking up the pen) and subsequent task demands (i.e. removing the lid) as second-order planning. This is distinctly different from first-order planning which Rosenbaum et al. (2012) suggest includes planning for immediate task demands only (such as ensuring the finger and thumb are far enough apart to pick up the pen). The Rosenbaum et al. (2012) review primarily uses the end-state-comfort (ESC) effect as an example of second-order planning. The most commonly used example of this effect is that of an upturned glass. In order to right the glass to its natural position and fill it with water from a jug, most adults will approach the glass with their thumb pointing downwards so that at the end of the movement the hand is in a comfortable position (Rosenbaum et al., 1990). This effect has been replicated in numerous studies focusing on child (Wilmut & Byrne, 2014) and young adult cohorts (Rosenbaum, Cohen, Meulenbroak, & Vaughan, 2006; Rosenbaum et al., 1990; Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993) and demonstrates that these groups are able to use second-order planning in order to make their movements optimally efficient.

Second-order planning such as that described above can be considered in tasks outside end-state-comfort which is typically measured with a dichotomous variable (end position comfortable or uncomfortable). For example, we can consider how second-order planning influences movement kinematics. Marteniuk, MacKenzie, Jeannerod, Athenes and Dugas (1987) asked participants to either reach and ‘fit’ a disc into a hole or reach and ‘throw’ the object. Despite the fact that initial demands of the reach component were identical across conditions, an elongated deceleration phase was seen for the reach movement which preceded a ‘fit’ action compared to a ‘throw’ action (Marteniuk et al., 1987). Jeannerod (2006) refers to the ‘why’ of a reaching action (i.e. the goal) as the *prior intention* of reaching. For example, in Marteniuk et al.’s (1987) study ‘fitting’ the disc and ‘throwing’ the disc are the two prior intentions of reaching. This term has been adopted in a recent review (Egmose & Køppe, 2018) and so will also be used here. Marteniuk et al. (1987) explain these differences in terms of the level of precision required in the prior intention; the higher the precision requirements of the prior intention (higher in the ‘fit’ versus the ‘throw’) the longer the deceleration phase of the reaching movement. This is essentially an extension of Fitts’ law (Fitts, 1954), which states that a smaller target (one needing a higher precision of movement) takes longer to point to than a larger one (Egmose & Køppe, 2018). This is supported by the finding that the deceleration period during the reach preceding a place with high precision requirements (tight-fit hole) is longer than that preceding a place with low-precision requirements (loose-fit hole) in both adults and older children (Wilmut, Byrne, & Barnett, 2013b).

Although the precision hypothesis might describe the conditions under which the deceleration phase extends it does not explain the *reason* this happens. One explanation for the change in deceleration period focuses on classical models of motor control, with the initial stages of a movement (prior to peak velocity) being pre-programmed or under feedforward control and the latter part of a movement (after peak velocity) being an online-control phase (feedback) where the movement can be updated or adjusted where appropriate (Desmurget & Grafton, 2000; Goodale, Pellision, & Prablanc, 1986). The changes seen during the deceleration phase of a reach movement (which fall under feedback/online control) are thought to be caused by the online planning of the upcoming prior intention. As more complex movements take longer to plan (Thompson, McConnel, Slocum, & Bohan, 2007) the deceleration period preceding a 'place' is elongated to a greater extent than that preceding a 'throw'. This conclusion would suggest that a prior intention is only planned towards the end of the preceding reach movement. However, a handful of studies have *also* demonstrated differences in the ballistic stage (the feedforward stage) of the reaching movement when comparing across prior intentions (Gentilucci, Negrotti, & Gangitano, 1997; Naish, Reader, Houston-Price, Bremner, & Holmes, 2013; Wilmut, Byrne, & Barnett, 2013a). This finding suggests that the prior intention is planned prior to the execution of the reach movement. Taking these studies in combination, it would seem that young adults plan for prior intentions both before movement execution and during a reach movement.

Previous studies have considered the functionality of this second-order planning with findings demonstrating that the degree to which the deceleration phase was tailored to the prior intention predicted the efficiency (the time spent adjusting the movement prior to placement of the object) of the place movements (Wilmut & Barnett, 2014; Wilmut et al., 2013a, 2013b). These findings suggest a possible purpose of tailoring one movement to the next whereby anticipating the appropriate action for both the first and the second movement results in a more efficient second movement.

When considering second-order planning in later life, a handful of studies have used end-state-comfort tasks which demonstrating an apparent change in older adults' ability to plan for the end of a movement and hence a decline in one's ability to demonstrate second-order planning (for example see Stöckel, Wunsch, & Hughes, 2017; Wang & Wilmut, Submitted). A change such as this could be explained by the quality or application of internal models which are thought to predict the consequence of action (Wolpert & Kawato, 1998). It is thought that the nervous system uses a copy of an impending motor command (efference copy or an internal model) to predict both the kinematic and sensory consequences of an action, this serves as a predictive estimate and allows for real-time monitoring and correction of movement where necessary (Desmurget & Grafton, 2000; Wolpert, Diedrichsen, & Flanagan, 2011). Essentially this is the basis for feedback control, with ongoing movement compared to the predicted outcome and where a mismatch occurs a correction is generated (Castiello, 2005; Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991). If these internal models become less accurate so does one's ability to control movement and one's ability to make predictions about the consequence of action prior to movement execution. In older adults we see an apparent decline in the ability to perform motor imagery tasks (Saimpont, Malouin, Tousignant, & Jackson, 2013; Skoura, Papaxanthis, Vinter, & Pozzo, 2005) and given the strong relationship between these tasks and internal modelling capacity (Jeannerod, 2001; Munzert, Lorey, & Zentgraf, 2009) it may follow that older adults use internal models less efficiently. This in turn would influence second-order planning as in order to take subsequent task demands into account and integrate these into a motor plan / executed action one needs to be able to predict the outcome of action and determine necessary requirements of action. We see this in the end-state-comfort task, in order to select a grasp for end comfort one needs to be able to predict what a given movement will do to the position of the hand. In the prior intentions tasks, in order to generate one movement (a reach) which take subsequent movements into account (prior intention) the consequence of one movement, whether it is to be executed or is being executed, is vital for accurate movement control and this is true whether we see changes for different prior intentions in the feedforward or feedback stage of movement.

When considering planning for prior intention in older adults a single study found that both young (22 years) and older (69 years) adults demonstrated an elongated deceleration phase when reaching for a target with the prior intention to place as compared to throw (Weir, MacDonald, Mallat, Leavitt, & Roy, 1998). However, no interaction was found between age and task indicating that the change in kinematics across task was the same for both age groups. This seems to argue against a deficit in second-order motor planning in older adults. However, as demonstrated by Wilmut and Barnett (2014), young adults demonstrate an ability to tailor movements to the precision requirements of the prior intention and this level of second-order planning may not be preserved in aging. Therefore, the primary aim of the current study was to look at second-order planning across a range of prior intention tasks including place movements with different levels of precision requirements (tight place versus loose place), this allowed us to determine whether older-adults discriminate between very similar prior intentions when planning a movement. Many studies which consider movement in older adults only consider a young versus an older adult group which may mean differences occurring earlier are missed. Therefore, this study compared second-order planning across the adult life-span, from 20 years of age to 80 years of age. Second-order planning was considered using a number of kinematic variables which described the entire movement (movement duration and peak velocity), the ballistic, pre-programmed stage of movement (time to peak acceleration), the online control phase (deceleration period). It was expected that young adults (20-40 years of age) would show second-order planning across all of these variables and for all of the movement types (Gentilucci et al., 1997; Marteniuk et al., 1987; Wilmut & Barnett, 2014). Furthermore, we expected to see some evidence of second-order planning from 40 years of age but that this would be different from 60 years of age (Weir et al., 1998). Whether differences are seen in which kinematic variables vary across movement types or which movement types vary from each other remained to be seen. Once second-order planning across the lifespan had been described we attempted to determine the importance of second-order planning in movement efficiency. Other variables which are thought to influence movement efficiency were also considered such as age, motor ability and movement speed.

Method

Participants

One hundred and twenty-two adults aged from 20 to 81 years of age were recruited from Oxford Brookes University and the surrounding area. Participants were grouped into six age groups (20-29, 30-39, 40-49, 50-59, 60-69, 70-81). All participants had normal or corrected-to-normal eyesight and were free from known movement difficulties related to neurological deficit or comorbid condition. Hand preference was determined by asking about writing hand. Ethical approval was granted by the University Research Ethics Committee at Oxford Brookes University. Full participant details can be found in Table 1.

---Table 1 ---

Task and procedure

Participants sat at a table in front of a Perspex cylinder 55 mm in height and 25 mm in diameter which was placed 0.3 times arm length in front of a start node which was to be grasped between the thumb and index finger of the preferred hand at the start of each trial. One of four ‘target’ objects was placed in full view of the participant 0.2 times total arm length behind and to the right of the cylinder for left-handed participants and behind and to the left for right-handed participants (see Figure. 1 for exact locations). Participants were instructed to grasp the start node and when instructed to reach out, grasp the cylinder and then perform one of four possible actions: place the cylinder in a hole 25mm in diameter (tight place), place the cylinder in a hole 40mm in diameter (loose place), lift the cylinder to the height of a 300mm dowel (lift) or throw the cylinder into 130mm diameter tray (throw). Each action was explained to the participant before the start of the experiment and on each trial the necessary movement type was cued by the target object and by a verbal command given by the experimenter. A Vicon 3D motion capture system (Oxford Metrics, United Kingdom), consisting of six infra-red cameras and running at 120 Hz, was used to track the movement of four reflective markers (6 mm in diameter) placed on the thumb (on the upper side of the nail plate when hands are placed palm down on a desk), index finger (on the nail plate), knuckle (of the index finger) and wrist (head of the ulna) of the preferred hand. A fifth marker was placed centrally on top of the cylinder. Each participant performed 8 trials for each action type and these were presented in a pseudo-randomised order. Once the action had been completed participants were instructed to return their hand to the start node and ready themselves for another trial. In order to determine general motor ability participants also completed the short version of the Bruininks Motor Ability Test (BMAT; Bruininks & Bruininks, 2012).

----Figure 1----

Data analysis

VICON hand movement data were filtered with an optimized Woltring filter (low pass 12 Hz), and tailored MATLAB® routines were used for analysis. Hand movement onset was determined using the wrist marker and defined as the time point at which velocity departed from zero (>3 % max velocity) and hand movement offset as the point velocity returned to zero (<3 % max velocity). From these time points four kinematic measures of the initial reach movement (i.e. from the start node to the cylinder) were calculated: 1. movement duration (ms), the time between movement onset and movement offset; 2. peak velocity (ms^{-1}), maximum velocity between hand movement onset and offset; 3. time to peak acceleration (ms), the time from movement onset until the point of maximum acceleration prior to peak velocity; and 4. deceleration period (%), time between peak velocity and movement offset as a percentage of movement duration. A single measure was extracted for the prior intention phase (i.e. from the cylinder to the target object); discontinuities in the velocity profile towards the end of a movement indicate that an individual has corrected an impending error (Khan et al. 2006); therefore, the movement time following a discontinuity (or adjustment) can be used as an inverse measure of planning efficiency. In order to determine undershoot adjustments we inspected zero-order crossings of acceleration of the cylinder marker while the hand was still in contact with the cylinder. This method of measuring adjustments has been adopted in previous reach-to-grasp studies (Rand et al. 2000; Seidler and Stelmach 2000). The time between the first secondary peak and movement offset was defined as adjustment time (ms). In all cases, these zero-order crossings always occurred after peak deceleration and where no zero-order crossing were apparent adjustment time was set to zero. Calculation of this variable was only possible for the 'place movements' as throw movements are not adjusted in the same way.

BMAT scores were not converted to standard scores as these are not available for the entire age range of participants included in this study. Data from 'mark shapes' (time taken to cross 6 circles) and 'transfer pennies' (number of pennies transferred from one hand to another and placed in 20 seconds) were used as they refer to fine motor skill which is most appropriate for the tasks in the current study. Raw scores were used to ensure an adequate level of measurement in order to detect within group differences.

Results

Statistical analysis

Each kinematic variable for the four movement types and across the six age groups was compared using mixed measures 4 x 6 way ANOVA (movement type x age group). Where sphericity was violated Greenhouse-Geisser corrected values are reported. Significant main effects were followed up using post-hoc comparisons with Sidak correction to control for Type I error. Significant interactions were followed up with simple main effects tests using univariate analysis. Reported effect size is generalised eta squared.

Kinematics of movement

Kinematics describing overall movement (movement duration) A significant main effect of movement type was found *F*(3,348) = 101.11, $p < .001$, $\eta_G^2 = .47$ with duration of a reach movement preceding a throw (*M* = 615, *SD* = 113) being shorter than that for a loose place (*M* = 634, *SD* = 116) which in turn was shorter than for a tight place (*M* = 649, *SD* = 116) which was shorter than for a lift movement (*M* = 681, *SD* = 117) (throw < loose place < tight place < lift). The effect of age group and the interaction between movement type and age group were not significant (*p* = .687 and *p* = .286 respectively). Data can be found in Table 2 and effects described in Table 3

---Table 2---

---Table 3---

Kinematics describing the ballistic phase of movement (peak velocity and time to peak acceleration) For peak velocity a significant main effect of movement type was found *F*(3,348) = 40.03, $p < .001$, $\eta_G^2 = .26$ with reaching movements preceding a throw action (*M* = 6.33, *SD* = 1.13) showing the highest peak velocity followed by the place movements (tight, *M* = 6.17, *SD* = 108 loose, *M* = 6.22, *SD* = 1.08) where no difference was seen and reach movement preceding a lift action (*M* = 6.05, *SD* = 1.05) showing the lowest peak velocity (throw > tight place = loose place > lift). The interaction between movement type and age group was also significant, *F*(15,348) = 2.31, $p = .005$, $\eta_G^2 = .09$. This interaction was investigated using simple main effects. All of the age groups, aside from the 20s (p = .377) demonstrated a significant effect of movement type, 30s $F(3,348) = 6.06$, $p < .001$, $\eta_G^2 = .05$; 40s $F(3,348) = 23.80$, $p < .001$, $\eta_G^2 = .17$; 50s $F(3,348) = 11.56$, $p < .001$, $\eta_G^2 = .09$; 60s $F(3,348) = 4.59$, $p = .004$, $\eta_G^2=.04$; 70+ $F(3,114) = 4.63$, $p = .003$, $\eta_G^2 = .04$. In the 30s group this was due to a higher peak velocity in a reach preceding a loose place (*M* = 6.18, *SD* = .75) or throw (*M* = 6.24, *SD* = .81) action compared to a lift action (*M* = 5.98, *SD* = .68). In the 40s and 50s group this was due to a higher peak velocity in a reach preceding a throw action (40s *M* = 6.70, *SD* = 1.45, 50s *M* = 6.73, *SD* = 1.28) compared to a loose (40s *M* = 6.53, *SD* = 1.43, 50s *M* = 6.54, *SD* = 1.18) or tight (40s *M* = 6.47, *SD* = 1.37, 50s *M* = 6.54, *SD* = 1.18) place action and a higher peak velocity in the reach preceding the place actions (see above) compared to the lift action (40s *M* = 6.17, *SD* = 1.27, 50s *M* = 6.35, *SD* = 1.24). Finally in the 60s and 70+ group this was due to a higher peak velocity in a reach preceding a throw (60s *M* = 5.97, *SD* = .85, 70+ *M* = 6.15, *SD* = 1.27) compared to a lift action (60s *M* = 5.73, *SD* = .83, 70+ *M* = 5.91, *SD* = 1.24). These across movement type effects are illustrated in Figure 2 and summarised in Table 3. There was no significant effect of age $p = .363$.

In terms of time to peak acceleration a significant main effect of movement type was found $F(3,348) = 4.23$, $p = .006$, $\eta_G^2 = .04$, with an earlier peak acceleration in a reach movement preceding a loose place action (*M* = 142, *SD* = 44.87) compared to a lift action (*M* = 152, *SD* = 45.50). The interaction between movement type and age group was also significant: $F(15,348) = 2.02$, $p = .013$, $\eta_G^2=.08$. This interaction was investigated using simple main effects. Only the 20s group demonstrated a significant effect of movement type, $F(3,348) = 7.93$, $p < .001$, $\eta_G^2 = .06$, which was due to an earlier peak acceleration for the reach preceding a tight place (*M* = 148, *SD* = 41.87) and loose place action (*M* = 147, *SD* = 43.21) as compared to the reach preceding a lift action (*M* = 175, *SD* = 44.62). These across movement type effects are illustrated in Figure 2 and summarised in Table 3. No significant age effect was found $p = .114$.

Kinematics describing the online phase of movement (deceleration period) A significant main effect of movement type was found $F(3,348) = 44.44$, $p < .001$, $\eta_G^2 = .28$ with a reach preceding a lift action ($M = 50.87$, $SD = 4.66$) showing the longest deceleration period followed by the tight place action ($M = 49.83$, $SD = 4.31$), followed by the loose place action ($M = 49.20$, $SD = 4.50$) and the reach preceding a throw action ($M = 47.50$, $SD = 5.57$) showing the shortest deceleration period (lift > tight place > loose place > throw). A main effect of age was also found, $F(5,116) = 2.90$, $p = .017$, $\eta_G^2 = .11$, with the 30-39 year group ($M = 47.48$, $SD = 5.45$) showing shorter deceleration periods compared to the 70+ age group ($M = 52.18$, $SD = 3.84$). The interaction between movement type and age group was also significant, $F(15,348) = 2.03$, $p = .026$, $\eta_G^2 = .08$. This interaction was investigated using simple main effects. All of the age groups, aside from the 70+ years ($p = .151$) demonstrated a significant effect of movement type: 20s $F(3,348) = 9.33$, $p < .001$, $\eta_G^2 = .07$, 30s $F(3,348) = 11.45$, $p < .001$, $\eta_G^2 = .09$, 40s $F(3,348) = 14.22$, $p < .001$, $\eta_G^2 = .11$, 50s $F(3,348) = 7.69$, $p < .001$, $\eta_G^2 = .06$, 60s $F(3,348) = 40.37$, $p < .001$, $\eta_G^2 = .26$. In the 20s and 30s groups this difference was due to a longer deceleration period in the reach movement preceding a lift (20s $M = 48.85$, $SD = 3.05$, 30s $M = 48.66$, $SD = 3.94$) or tight place (20s $M = 49.61$, $SD = 3.42$, 30s $M = 48.89$, $SD = 4.02$) versus a loose place (20s $M = 47.79$, $SD = 3.69$, 30s $M = 47.04$, $SD = 5.19$) or throw (20s $M = 46.24$, $SD = 3.19$, 30s $M = 45.33$, $SD = 6.14$). In the 40s, 50s and 60s this was due to a longer deceleration phase in the reach preceding a lift action (40s $M = 51.43$, $SD = 4.97$, 50s $M = 50.83$, $SD = 4.67$, 60s $M = 52.29$, $SD = 3.35$), a tight place (40s $M = 49.31$, $SD = 5.32$, 50s $M = 49.31$, $SD = 4.25$, 60s $M = 49.89$, $SD = 3.94$) or loose a place action (40s $M = 48.99$, $SD = 5.54$, 50s $M = 49.24$, $SD = 4.18$, 60s $M = 50.15$, *SD*

= 3.75) versus a reach preceding a throw action (40s *M* = 47.04, *SD* = 7.04, 50s *M* = 46.24, *SD* = 6.65, 60s *M* = 48.24, *SD* = 4.91). These across movement type effects are illustrated in Figure 2 and summarised in Table 3.

----Figure 2----

Kinematics describing place prior intentions (adjustment time) A significant main effect of movement type was found $F(1,116) = 34.14$, $p < .001$, $\eta_G^2 = .23$ and age group $F(5,116) = 5.00$, $p < .001$, $\eta_G^2 = .18$. These differences were due to longer adjustment times for tight place (*M* = 13.45, *SD* = 7.14) versus loose place movements (*M* = 9.59, *SD* = 5.89) and longer adjustment times in the 60s and 70+ groups (60s *M* = 14.72, *SD* = 7.72, 70+ *M* = 14.44, *SD* = 6.22) compared to the 20s and 30s age group (20s *M* = 8.94, *SD* = 5.51, 30s *M* = 8.47, *SD* = 5.91) (60s = 70+ > 20s = 30s). These across movement type effects are summarised in Table 3. No significant interaction between age group and movement type was found ($p = .603$). See Figure 3 for an illustration of these effects.

----Figure 3----

Relationship between tailoring of a reach movement and prior intention

In order to consider the relationship between reach and prior intention movement we calculated the difference in deceleration period during a reach movement across the two place movements as a proxy of second-order movement planning (i.e. the degree to which an individual tailors a reach movement to the prior intention action). The change in proportion spent decelerating across action types measures the degree to which a reach to one prior intention (loose place) differs from a reach to a different prior intention (tight place). If a participant showed a deceleration period for a tight place action of 50% and for a loose place action of 40%, then the change would be 10%. This could then be compared to another participant who may have shown more (12%) or less (1%) discrimination between the reach movements for the different prior intention actions. A similar measure for the difference in movement duration was also calculated. The relationship between these variable (difference in deceleration period and difference in movement duration) and adjustment time and age was then considered using Pearson Correlation tests on the entire cohort. In addition, we looked at the relationship between age and adjustment time and fine motor skill as measured by the BMAT (BMAT mark shapes, BMAT transfer) and movement duration (average movement duration across the lift and the throw action[1]). All correlation coefficients and corresponding alpha values can be found in Table 4.

A significant correlation between age and difference in deceleration period was found demonstrating that as age increased the difference in deceleration period decreased. No such relationship between age and difference in movement duration was found. We also found a significant relationship between difference in deceleration period and adjustment time, whereby as the difference in deceleration period decreased adjustment time increased. No relationship was found between adjustment time and difference in movement duration was found. Fine motor skill and movement duration also showed significant relationships with both age and adjustment time.

---Table 4---

What mediates the effect between age and movement efficiency?

[1] This was used as a measure of general movement speed as it was considered to have no direct influence on movement efficiency, movement duration of the reach preceding a place movements might have, while allowing for a between-participant consideration of natural reaching speed.

In the previous section we considered the relationship between adjustment time, second-order planning, fine motor skill, movement duration. In this section we are interested to determine which variables mediate the relationship between age and adjustment time (movement efficiency). The mediation analysis was done using model 4 of the PROCESS macro in SPSS (Hayes, 2012) which uses the bootstrapping method to explore indirect effects. Age was entered as the predictor variable, fine motor skill, movement and a measure of second order planning (specifically changes in deceleration period) were entered as parallel mediators in order to compare the indirect effects, and adjustment time was entered as the outcome variable. The confidence intervals for the indirect effects were bias corrected and accelerated (BCa) based on 10000 samples. Prior to the mediation analysis zero-order correlations between these variables and movement efficiency were conducted and these can be found in Table 4. The measure of second-order planning (difference in deceleration time) was the only significant mediator on the relationship between age and adjustment time (see Table 5 for details). However, once the effects of these mediator variables had been removed age still predicted adjustment time ($F(1,120) = 26.48$, $p < .001$, $R^2 = .18$, beta=.0015), demonstrating that as age increases so does adjustment time. This effect is illustrated in Figure 4.

---Figure 4---

---Table 5---

Discussion

The aim of this study was to provide a comprehensive analysis of second-order planning for prior intentions across the adult-lifespan. In order to examine this, we asked participants from 20 to 81 years of age to complete a two-phase task with four different prior intentions allowing us to study second-order planning as kinematic changes in the reaching movement reflects planning for different prior intentions. When considering the initial reach movement we have demonstrated clear second-order planning in all groups of participants thus demonstrating second-order planning is present in old age. However, it would seem that this changes somewhat as we grow older.

We took four measures of kinematic control of the reaching movement, one describes the entire reaching movement and is due to both feedback and feedforward control (movement duration), two describes the ballistic phase of movement under feedforward control (peak velocity and time to peak acceleration), one describes the adjustment phase of movement under feedback control (deceleration period). All four of these showed some aspect of adjustment based on prior intention. Movement duration had the same pattern of adjustment across the prior intentions for all age groups, with a general pattern that for prior intentions where movement duration was shorter (throw < loose place < tight place < lift). A change in movement duration across prior intentions is in line with previous studies (Egmose & Køppe, 2018; Marteniuk et al., 1987; Wilmut et al., 2013a). It was the other three kinematic measures (peak velocity, time to peak acceleration and deceleration period) where we saw marked differences between the age groups in terms of second-order planning for prior intention. Only the youngest group showed discrimination in time to peak acceleration for the reaching movement preceding the differing prior intentions, with the place movement showing an earlier peak acceleration than the lift. Peak velocity differed in the reaching movement for all age groups aside from the youngest, with peak velocity for the reaching movement preceding a throw typically being higher than that for the lift or place. For deceleration period the 20-39 year-olds discriminated between tight and loose place as has been shown in this age group previously (Wilmut & Barnett, 2014; Wilmut et al., 2013a).

The 40-69 year-olds discriminated between place and throw which is most commonly found (Egmose & Køppe, 2018; Marteniuk et al., 1987; Weir et al., 1998) but lacked the discrimination between the two place movements. Finally the 70+ group demonstrated no change in deceleration periods for any of the four prior intentions. The latter two of these being novel findings.

As a whole these results support the precision hypothesis, with prior intentions requiring a greater precision (i.e. tight place over loose place) showing a longer deceleration period. Changes in the ballistic phase and the adjustment phase of the reaching movement suggests that this second-order planning for prior intentions does, at least in our youngest group, start prior to movement execution. Changes within the ballistic phase have been demonstrated previously (Gentilucci et al., 1997; Naish et al., 2013; Wilmut et al., 2013a) but the novel finding here is that these very early kinematic changes may be isolated to young adults only, something which was missed in previous studies as they all focused on young adult populations (mean age ~ 26years). Our data suggest that between 29 years of age and 69 years of age, second-order planning is isolated to the online phase of movement. After 69 years of age there seems no clear indication of when the second-order planning occurs, but rather we see changes in measures across the entire movement interestingly this mirrors the pattern seen in young children (Claxton, Keen, & McCarty, 2003; Wilmut & Byrne, 2014).

Two factor which have not been discussed thus far but could help to describe second-order planning are: reaction time, i.e. how long one takes to plan a movement; and dwell time i.e. how long one spends pausing between the reach and the prior intention. One could plan both the reach movement and the prior intention before initiating any movement, if this were the case we would expect to see reaction time differences across prior intentions. Equally one could complete the task without engaging in second-order planning and could plan the prior intention after the reach movement had been completed, if this were the case we would expect to see differences in the dwell time across age groups. Neither of these measures is commonly measured in this task, however, when consider age-related differences both do need consideration. In the current study we did measure dwell time and we saw no age-related, movement type related or interaction effects. This would strongly suggest that none of the groups planned the prior intention after completing the reach movement or in other words it would suggest that all participants engaged in second-order planning. In contrast, we did not measure reaction time and so older adults may have taken longer to plan for some prior intentions over other prior intentions, this would still represent second-order planning but would not be seen in the kinematics for movement. Whether or not such a difference is seen could be a consideration for future research. What is apparent from the current study, however, is a clear change in second-order planning across the lifespan.

The only previous study which considered second-order planning for prior intentions in older adults was (Weir et al., 1998) who used a place action and a throw action and although they found an elongated deceleration period for the reaching movement preceding the place as compared to the throw this was present in both groups. Therefore, suggesting that second-order planning does not differ in older adults compared to young adults. This contrasts to the findings of the current study but can be explained in by considering the age groups used. In the current study adults up to 69 years of age demonstrated an elongated deceleration period for the reaching movement preceding a place as compared to a throw. The average age of the older adults in Weir et al.'s (1998) study was 69.25 years ±0.25 years, therefore, Weir's group were aligned with the upper range of our 60-69 year-old group and the lower range of our 70+ group. Therefore, our data essentially extend (Weir et al., 1998) findings and demonstrate a difference in second-order planning during advanced aging which has previously been missed. Our data also demonstrate that this difference in second-order planning occurs much earlier than 70 years of age. In fact, we see a difference in the way adults plan for prior intentions from 40 years, when adults no longer seem to tailor deceleration period to prior intention when the prior intention is a tight place as compared to a loose place action. This precision in planning to the same general action, but with very different requirements, seems only to be present prior to 40 years of age.

We have suggested that a prior intention might be planned during the reach movement and where precision requirements are high (place the object into a tight hole) this planning takes longer and thus elongates the deceleration period over and above reach movements where the prior intention has lower precision requirements (place into a loose hole). If this is the case then where we fail to see change in deceleration period across tight place and loose place actions it would seem that planning time may either be cut short for tight place prior intentions or too long in loose place prior intentions and this would be expected to impact on the kinematics of the subsequent movement, e.g. placing the object into a hole. In a previous paper we have shown a relationship between how much one discriminates between tight and loose place in terms of the deceleration period of the preceding reach movement and subsequent movement efficiency (Wilmut et al., 2013a, 2013b). We replicated this finding in the current paper, showing that the degree of discrimination between the deceleration period for the tight place versus the loose place prior intention was related to the movement efficiency time for that participant and that this effect was independent of age.

In the introduction we highlighted the importance of internal models in second-order planning and suggested this as a mechanism through which older adults may change the way in which they demonstrate second-order planning if they are showing age-related deficits with internal models. This study did not directly measure internal models and so we cannot make any inferences about how these are used across the lifespan. However, our age-related differences in second-order planning might hint towards changes or plausibly deficits in the internal modelling system in older adults. If we unpack the kinematic changes we see that the

20-69 year-olds show changes in response to different prior intentions in both the feedforward (ballistic) and feedback (online control) phase of movement. In contrast, the 70+ age group only show changes in the feedforward (ballistic) phase of movement. Internal modelling provides an important predictive mechanism for movement control and is vital in feedback control, where a predicted outcome of a movement is compared to the actual outcome at all stages of the movement and the movement is updated if a disparity occurs. In addition to the apparent decline in motor imagery in older adults studies have demonstrated a change in feedback control (for example see Coats & Wann 2011, for a discussion on the reliance on visual feedback during online control) and so this may account for the shift away from second-order planning change during the online control or feedback control stage of movement.

Further to this we considered factors which may mediate the relationship between age and adjustment time (or movement efficiency). It was found that this relationship was mediated by second-order planning (but not fine motor skill or movement duration). Individuals who demonstrated a greater discrimination between the deceleration of the reach preceding the two place movements showed a higher level of movement efficiency, i.e. less overall adjustment time for the place actions. It would seem from this that second-order planning is most effective (i.e. movement efficiency is at its highest) we see a change in the length of the deceleration period of the preceding reach action. This finding demonstrates the importance of second-order planning in the feedback stage of a reach movement to ensure movement efficiency. Therefore, the shift away from this type of second-order planning in older adulthood may, to some extent, explain the loss of movement efficiency.

In conclusion, for the first time, the current study has demonstrated second-order planning for prior intention across the lifespan. Second-order planning plays an important role in conducting fluent sequential movements, where effective planning in the imminent action ensures an efficient movement in the subsequent action. This effect is independent of age, which demonstrates a general role of movement planning across the adult lifespan. However, the nature of this second order planning seems to differ as we get older, in particular when the planning needs to be tailored to intended actions that are similar to each other but require different levels of precision to achieve, e.g. place in a tight-fit hole versus a loose-fit hole. More importantly, this difference is not isolated to the very old, but rather starts around 40 years of age that the ability to plan for a high level of specificity starts to show gradual declines. With advanced aging (over 70), the second order planning for prior intentions becomes less obvious and leads to less efficient subsequent movements but does not disappear altogether.

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