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End-State-Comfort in typically developing children; a developmental trajectory

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Abstract

When reaching towards an object, adults favour grasps which, following the intended action, end in a comfortable position even when this requires them to start in an uncomfortable position. This has been termed the end-state-comfort-effect. Several studies have found the end-state-comfort effect in children as young as 4 year or age. However, the exact developmental time course of this skill is unknown. Even though the majority of movements we make in everyday life are multi-staged movements, studies considering the end-state-comfort effect have only considered a single movement. The current study considered grip selection in children ranging from 4-11 years and in a group of adults. Participants were asked to rotate a disc so an arrow pointed towards a specific target(s), the number of sequences in a movement was increased from one to three. Planning for end-state-comfort was seen in all participants and the number of movements ending in comfort could be predicted by age in months. Data indicated that where the youngest children were not using movements which ended in comfort this may have been due to favouring a grasp which required a much smaller initial rotation. Although differences across sequence lengths were observed, with the end-state-comfort effect being less frequent for longer sequence lengths, this pattern of change across sequence length was the same for all of the age groups.

Introduction

The seemingly simple actions we perform in everyday life actually require a great deal of planning and consideration regarding their outcome. Manual movements such as deciding how to grasp an object are influenced by the end position we will find ourselves in. Adults, as skilled movers, perform such actions with relative ease and this kind of forward anticipation allows for skilful control of successive movements (Herbert & Butz, 2011) as well as minimising fatigue and maximising comfort (Haggard, 1998; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992). One example of this kind of anticipation in motor planning is the end-state-comfort effect (Rosenbaum et al., 1990) whereby an uncomfortable start position is chosen in order that the end result is comfortable. 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 up with water from a jug, most adults will approach the glass with their thumb pointing down and their elbow pointing up so that at the end of the movement, when the precise action of pouring water into the glass takes place, the hand is in a comfortable position (Fischman, 1997). The end-state-comfort effect has been shown on many occasions in adult populations using a variety of tasks (for examples see Fischman, 1997; Rosenbaum et al., 1990; Rosenbaum et al., 1992). One common theme among these studies, however, is that selecting grips for end-state-comfort is not a rule, some adults do it less frequently than others and some adults don't seem to show the effect at all.

Several studies have considered the developmental time course for grasp selection. Using the example of the upturned glass and a jug of water, Adalbjornsson, Fischman, & Rudisill (2008) found that only 20% of 2-3 year-olds and 35% of 5-6 year-olds demonstrated an end-state-comfort effect. In this study, a child was specified as showing an end-state-comfort effect if they picked up the glass using an awkward thumb down grasp on 2 out of 3 trials. Weigelt & Schack (2010) used the same dowel placing task developed by Rosenbaum et al. (1990) and assessed groups of 3, 4, and 5 year old children. They showed that on change trials where achieving end-state-comfort necessitated using an underhand grasp of the dowel (which is a more complex grasp) there was a clear improvement between the age groups with 18% of 3 year olds selecting such a grasp, 45% of 4 year olds and finally 67% of five year olds. Manoel & Moreira (2005) also used the dowel task to end-state-comfort in young children, however, they used two versions a high precision and a low precision version. The report *"there is no evidence for planning of increasing planning ability in the sample…….ranging from the age of 2.5years to 6years"* (Manoel & Moreira, 2005, pg 110). However, this was based on the end-state-comfort effect not being evident as would be expected from studies using this task in adults. Despite the seemingly lack of mature level of this skill, the data from the Manoel and Moreira study may still be evidence of end-state-comfort planning in young children.

These finding were extended by Smyth & Mason (1997) who considered end-state-comfort in a slightly older cohort of children, aged 4-8 years of age. They used both a dowel placing task and a rotation task designed to assess planning for end-state-comfort. Their results indicated that the ability to use grasps for end-state-comfort developed between the ages of 4-8 years of age, with 4-5 year-olds selecting grasps for end-state-comfort on approximately 58% of trials and 7-8 year-olds on approximately 67% of trials. Although Smyth & Mason (1997) report the percentage of trials where end-state-comfort was achieved they do not report individual data so whether these figures refer to some children consistently selecting grips for end-state-comfort and others not or if all children select grips for end-state-comfort on some trials is unclear. Thibaut & Toussaint (2010) used a similar paradigm and classified children as showing the end-state-comfort effect if they selected a grip for end-state-comfort on 2 out of 3 trials (the criteria used by Adalbjornsson et al. 2008). 42% of 4 year-olds, 66% of 6 year-olds, 49% of 8 year-olds and 81% of 10 year-olds met this criterion for selecting grasps for end-state-comfort. Thibaut & Toussaint concluded that at 10 years of age the majority of children displayed the end-state-comfort effect as seen in adults and therefore possess a mature strategy to plan for end-state-comfort (an adult control group was reported to have been included, however, no data was presented). van Swieten et al. (2010) used a slightly different task to Thibaut & Toussaint (2010) and found that although, their group of 9-14 year old children showed a higher propensity towards selecting grasps for end-state-comfort, this propensity was still not on par with the adult group. However, 82% of the 9-14 year-olds were selecting grasps for end-state-comfort and this is very similar to the proportion of 10year-olds selecting grasps for end-state-comfort in the Thibault and Toussaint study. Therefore, whether a child group show a mature propensity to select grips for end comfort seems to be very task dependent. In addition to considering end-state-comfort van Swieten et al. (2010) also looked at other strategies for grip selection, specifically they considered whether a minimal rotation of the hand prior to contact with the object was favoured over finishing a movement in a comfortable position. In their set-up a child could either maximally rotate the hand at the start of a movement and finish in end-state-comfort or start a movement with minimal rotation and end in an uncomfortable position. Results indicated that a greater proportion of 5-8 year-old children were biased to select a minimal rotation grip compared to 9-14 year-olds.

All of the developmental studies discussed have shown some level of selecting grasps for end-state-comfort. The difficulty seems to be in classifying what level of this is expected. Do all the children in a group need to be selecting grips for end-state-comfort on every trial in order for their performance to be considered mature? One of the difficulties with the previous studies is that many have not included an adult reference group and given that we know that adults do not always select grasps for end-state-comfort this makes drawing conclusions difficult. The current study aims to consider planning of end-state-comfort in children aged between 4-10 years of age considering both the developmental trajectory of this skill and how they compare to an adult reference group. Data will be presented both in terms of the percentage of *trials* where end-state-comfort is achieved but also the proportion of *participants* demonstrating a clear end-state-comfort effect. This study will also consider different strategies for selecting grips, namely whether young children favour a minimal rotation strategy. All of these aspects of selecting grips for end-state-comfort will be considered for a single movement (as has been done before) but also for a sequence of movements. Haggard (1998) has shown that adults are able to plan grips for two and three movement sequences. Extending the requirement to include two and three components increases the complexity and requires participants to plan a longer movement (Haggard, 1998).

For one sequence movements we would expect to see some level of selecting grips for end-state-comfort in all of the age groups, in addition, we would expect to see a developmental improvement in this skill (as has been demonstrated previously; Smyth & Mason, 1997; Thibaut & Toussaint, 2010; van Swieten et al., 2010). We would also expect that younger children would favour a minimal rotation strategy over an end-state-comfort strategy. For multiple movement sequences, we would expect adults to, on the whole select grasps for end-state-comfort given that Haggard (1998) has shown that adults are able to plan for the final movement of a three-step movement. Whether children show a similar pattern and whether this develops at the same rate as selecting grips for one-step movements is unclear.

Method

Participants

Twelve typical adults (mean age: 26 years, 6 months, age range: 18 years, 8 months: 39 years, 5 moths), 4 males and 8 females were recruited from Oxford Brookes University to take part in this study. Forty-eight children (28 girls and 20 boys) from four age groups (all N = 12) took part in the study. The mean age of the 10-11 year olds was 10 years, 4 months (age range: 10 years: 11 years, 7 months), of the 8-9 year olds was 8 years, three months (age range: 8 years: 9 years, 11 months), of the 6-7 year olds was 6 years, 4 months (age range: 6 years: 7 years, 10 months) and of the 4-5 year olds was 4 years, 7 months (age range: 4 years: 5 years, 10 months). All children were recruited from local schools and research group networks at Oxford Brookes University. To ensure that no participants had movement difficulties individual movement assessments were carried out. Adults were assessed on the age band three manual dexterity component of the Movement Assessment Battery for Children 2nd Edition (MABC-2; Henderson, Sugden, & Barnett, 2007). Although this assessment is not designed for an adult population a good performance, alongside self report of a lack of motor difficulties can be taken as an indication of a typical motor ability. All adults scored above the 15th percentile. The children all completed the appropriate age band on the test component of the MABC-2 and all fell above the 9th percentile. Participant information is given in Table 1.

INSERT TABLE 1 HERE

Materials

Participants were seated in front of a wooden octagon mounted on a back board, the octagon was surrounded by 8 different colours. The size of the octagon to be grasped was varied depending on the size of the hand. The octagon could be rotated about its centre so that an arrow, initially pointing directly upwards, could be turned to point to one of the 8 colours on the board (see Figure 1 for an illustration of the set-up). A start node placed 0.3 times total arm length from the octagon was provided and participants were instructed to grasp this between their thumb and index finger prior to the start of each trial. All movements were video recorded.

INSERT FIGURE 1 HERE

Procedure

For each participant a baseline or neutral grasp was determined by asking the participant to grasp the octagon in a comfortable or neutral position, ensuring that each finger lay on a different side. Participants were then given a colour or a sequence of colours and instructed to grasp hold of the octagon and rotate it so that the arrow pointed to the colour(s) in the order they were listed. Each trial began with the participant grasping the start node between their thumb and forefinger. They were explicitly told that they should think about the way in which they grasped the octagon to ensure they could complete the movement. Rotation of the octagon could be done either in a clockwise or anti-clockwise direction or a combination of these directions for multiple colour sequences. Participants were instructed to ensure their fingers remained in contact with the octagon for the entirety of the movement and that they could not alter their grasp during the movement. All trials began with the participant grasping the start point between their thumb and forefinger. Sequences of one, two or three colours were used and all participants completed the shortest movements first moving up through the sequence lengths. The multiple colour sequences all included a movement to green which necessitated a 180° rotation. One sequence movements also included rotations to green but also to colours requiring a smaller rotation. The presentation of sequence order in blocked fashion rather than random allows both the children and adults to progress from the simplest task (one colour) to the most difficult (three colours). The disadvantage of this is that any between-group differences may be affected by learning. However, the advantage of this is it optimises the performance of the youngest children. There is no ideal trial ordering for testing children but we believe that a fixed presentation order is most appropriate for young children.

Judgements of end-state-comfort

In order to determine whether an end position was comfortable or not, the level of comfort for each possible end position was judged by an independent cohort of adults (15 right handers and 15 left handers aged between 18 and 30 years of age). These 'raters of comfort' were asked to place their thumb on each side of the octagon following both a clockwise and an anti-clockwise rotation and rate each of those hand positions on a 1-6 scale: very comfortable (1); slightly comfortable (2); neither comfortable nor uncomfortable (3); slightly uncomfortable (4); very uncomfortable (5); or impossible (6). Average judgements of each position were calculated separately for right and left handers and a position was taken as comfortable if the average score fell at or below 2 (slightly comfortable to very comfortable) and the standard deviation was below 1. This produced four positions for right handers and four positions for left handers that were deemed comfortable.

Data Analysis

Grasp positions were determined by watching the video recordings. For each grasp the positioning of the thumb was recorded (sides of the octagon were numbered 1-8 and so each thumb position was defined by one of these values, see Figure 1). In order to ensure reliability of coding hand position in this way 25% of participants were coded by a second coder. Inter-rater reliability analyses were carried out on the coded position of the thumb by the two raters. Cohen's Kappa showed excellent agreement between the two coders for adults [kappa=0.99

p<.001], 10-11 year-olds [kappa=0.96 p<.001], 8-9 year-olds [kappa=0.88 p<.001], 6-7 year-olds [kappa=0.95 p<.001] and 4-5 year-olds [kappa=0.96 p<.001]. One child in the 4-5 year old age group consistently changed her hand position while rotating the octagon, whether this was due to a misunderstanding of the task constraints or a lack of ability was not clear. This participant and her data were removed from the analysis.

The main measures taken for each movement were: *initial rotation of the thumb (degrees)* which refers to the amount of rotation of the hand from the start node to the initial grasp position on the octagon. Given the orientation of the thumb at the start node, placing the thumb on side '6' (or '5' for a left hander) required no rotation of the wrist, for each side of the octagon away from these positions the wrist would have rotated an additional 45°. This only resulted in an approximation of initial thumb rotation but allowed the comparison between a large rotation and a small rotation; *Percentage of initial rotation of the thumb movements,* using the initial rotation of the thumb each movement was classified as either a initial rotation movement or a no initial rotation movement, the proportion of these were calculated; *Percentage of End-state-comfort movements (%),* this was based on the end position of the thumb, this position could be judged as either comfortable or uncomfortable using the independent ratings of comfort. Each movement was classified in this way and then for each participant, a percentage of comfortable movements was calculated for one, two and three movement sequences. Therefore, a higher number here indicates a greater propensity to use a grip which ended in a comfortable movement; *Quantification of comfort,* each possible end position of thumb was given a rating from 1-6 for comfort thus giving an average comfort rating for each end position. Each movement was assigned this comfort rating on the basis of the end position of the thumb. Therefore, an average value of comfort of end position was calculated for each participant for one, two and three movement sequences. This value fell between 1 and 6 and a high value indicates a propensity to use grips ending in an uncomfortable position.

Results

End-State-Comfort

In this study there are two measures of end-state-comfort (ESC), the percentage of movements ending in ESC and the quantification of comfort for the end position. Initially the percentage of movements ending in ESC was analysed using a 2 x 3 factorial ANOVA (age group x sequence length); these data can be found in Figure 2. A significant effect of sequence length, [$F(2,108)=62.47$ $p<.001$ partial $\eta^2=.54$] was found, whereby a greater proportion of one sequence movements ended in ESC compared to two sequence movements and a greater proportion of two sequence movements ended in ESC compared to three sequence movements (1 sequence>2 sequence>3 sequence, all $p<0.05$ following Bonferroni correction). In addition, there was a main effect of age group [$F(1,54)=12.56$ $p<.001$ $\eta^2=.48$] which when further explored showed that the adults ended significantly more movements in ESC compared to all of the child groups and that the 10-11yr-olds and 8-9yr-olds ended more movements in ESC compared to the 6-7yr-olds and 4-5yr-olds (all $p<0.05$ following Bonferroni correction). No interaction between sequence length and age group was found. In terms of consistency for selecting grips for ESC previous studies (e.g. Thibaut & Toussaint, 2010; Adalbjornsson et al. 2008) have classified a child as selecting grips for end-state-comfort if they did this on 2/3 trials (equivalent to 66.6% of trials). We applied this criterion to our data and the corresponding number of participants in each group meeting this criterion can be found in Table 2. These values are similar to those found by van Sweiten (if considering just the one-step movement which is equivalent to their condition).

INSERT FIGURE 2 HERE

Secondly the quantification of comfort was considered using a 2 x 3 factorial ANOVA (age group x sequence length), these data can be found in Table 2. As with the percentage of movements ending in ESC a main effect of sequence length and age group was found, but no interaction between these variables was present. The main effect of sequence length, $F(2,108)=56.71$ $p<.001$ partial $\eta^2=.51$ was due to a greater proportion of one sequence movements ending in a more comfortable position in comparison to two sequence movements and a greater proportion of two sequence movements ended in a more comfortable position in comparison to three sequence movements. (1 sequence<2 sequence<3 sequence, all $p<0.05$ following Bonferroni correction). The main effect of age group, $F(1,54)=16.53$ $p<.001$ partial $\eta^2=.55$ was due to a significantly lower average comfort rating (i.e. more comfortable) for the adults compared to all of the child groups and a lower average comfort rating for the 1-11yrs and 8-9 yrs compared to the 6-7yrs and the 4-5 yrs (Adults < 10-11yrs = 8-9yrs < 6-7yrs = 4-5yrs, all $p<0.05$ following Bonferroni correction).

In order to more fully explore the developmental trajectory of ESC a regression analysis was carried out for each sequence length considering whether age in months predicted the percentage of movements ending in ESC. For this analysis the adult group was excluded as it was felt a significant result when looking at all the groups may solely be driven by the adults rather than a true reflection of the developmental time course in childhood Age predicted the percentage of movements ending in ESC for all three sequence lengths: one movement sequence, $F(1, 45)=11.45$ $p=.001$, $R^2=0.203$, $\beta=0.296$; two movement sequence $F(1,45)= 8.48$ $p=.006$, $R^2=0.159$, $\beta=0.24$; and three movement sequence $F(1, 45)=5.78$ $p=.02$, $R^2=0.114$, $\beta=0.18$. As age in months increases the percentage of movements ending in ESC also increases. A similar analysis was carried out to see whether age in months can predict the average quantification of comfort. Again a significant regression analysis for all three movement sequence lengths was found [$F(1,46)=12.33$ $p=.001$ $R^2=0.22$ $\beta=-.008$, $F(1,46)=20.59$ $p<.001$ $R^2=0.31$ $\beta=-.010$, $F(1,46)=10.26$ $p=.003$ $R^2=0.19$ $\beta=-.008$ respectively]. Age in months can predict the average comfort of end positions, as age increases end positions become more comfortable.

INSERT TABLE 2 HERE

Initial rotation of the thumb

The proportion of initial thumb rotation movements can be found in Table 2. A 2 x 3 factorial ANOVA (age group x sequence length) found no significant differences for either age group or sequence length. These results indicate that the children were not favouring a no initial rotation strategy more than the adults. In order to explore the initial rotation movements, the proportion of movements ending in ESC was calculated, this data can be seen in Table 2. A 2 x 3 factorial ANOVA (age group x sequence length) found a main effect of sequence length [$F(2, 108)=24.35$ $p<.001$ $\eta^2=.33$] whereby more one sequence movements with initial rotation of the thumb ended in end-state-comfort compared to two or three sequence movements ($p<0.05$ with Bonferroni correction). A main effect of age group and an interaction between age group and sequence length was also found [$F(4, 54)=7.17$ $p<.001$ $\eta^2=.35$ and $F(8,108)=3.17$ $p=.003$ $\eta^2=.19$]. When unpicking the interaction, the effect of age held for the one and two sequence movements [one movements: $F(4,45)=7.11 p<.001$, two movements: $F(4, 54)=10.86$ $p<.001$]. For one sequence movements adults, 10-11 year-olds and 8-9 year-olds showed a greater proportion of initial rotation movements ending in ESC compared to the 6-7 and 4-5 year-olds. For the two sequence movement the difference was between the adults and the children. No difference was seen for the three sequence movements (all $p<0.05$ following Bonferroni correction).

So although the adults and older children do not show a greater proportion of movements with initial thumb rotation, they do show a greater proportion of those rotation movements ending in ESC. The final analysis considered the magnitude of the initial thumb rotation movements. The average initial thumb rotation (excluding movements were no initial rotation was seen) was calculated and can be found in Table 2. A 2 x 3 factorial ANOVA (age group x sequence length) found a main effect of age group [$F(4,53)=8.08$ $p<.001$ $\eta^2=.38$], this was due to a greater initial thumb rotation in adults compared to 10-11year-olds and in 10-11year-olds compared to the other three child groups (adults > 10-11yrs > 8-9yrs = 6-7yrs = 4-5yrs all $p<0.05$ with Bonferroni correction). In order to fully explore this relationship Pearson correlations between the percentage of movements that ended in ESC and magnitude of initial thumb rotation were carried out for each sequence length. Significant positive correlations were seen for all three sequence lengths [one movement $r=.55$ $p<.001$, two movements $r=.72$

p<.001, three movements r=.70 p<.001] indicating that participants who had a higher initial thumb rotation ended a greater proportion of movements in ESC.

Discussion

Previous studies which have considered end-state-comfort in children have all reported some selection of grips that have ended in a comfortable position. However, the way in which these values were calculated and reported has varied. Some studies report the average percentage of trials ending in end-state-comfort (e.g. Smyth & Mason, 1997; Thibaut & Toussaint; 2010) while others report the proportion of participants ending a certain number of trials in end state comfort (e.g. all trials, van Sweiten et al., 2010; at least 2/3 trials, Adalbjornsson et al., 2008; Weigelt and Schack, 2010). In addition, some studies have included an adult comparison group, others have not. These differences across studies have made drawing conclusions difficult. The current study, once again found evidence for planning for end-state-comfort in all of the groups.

In terms of a comparison of across studies, if we first consider the average percentage of trials ending in comfort, Smyth and Mason (1997) report 58% of trials for 4-5year-olds and 67% for 7-8 year-olds. Thibaut & Toussaint (2010) report ~42% for 4year-olds, ~45% for 8 year-olds and ~80% for 10 year-olds (only the more complex underhand grips are reported here). In the current study we have shown 55% for 4-5 year-olds, 52% for 6-7 year-olds, 67% for 8-9 year-olds and 71% for 10-11 year-olds. Given the task differences across these studies these values are very similar and all support a developmental trend from 4 to 10 years of age. Secondly we can consider the percentage of participants consistently ending movements in end-state-comfort. This is only done for the criteria used by Adalbjornsson et al. (2008) of 2/3 trials. In the Adalbjornsson et al. (2008) study 20% of 2-3 year-olds and 35% of 5-6 year-olds consistently selected grasps for end-state-comfort. In the van-Sweiten (2010) study 81% of 10-14 year-olds and 50% of 5-8 year-olds consistently selected grasps for end-state-comfort. In the current study 92% of 10-11 year-olds, 50% of 8-9 year-olds, 25% of 6-7 year-olds and 18% of 4-5 year-olds consistently selected grasps for end-state-comfort. Again these values are very similar and again both the van Sweiten (2010) study and the current study support a clear developmental trend. If fact the current study found a clear developmental trajectory in terms of the average proportion of grasps for end-state-comfort, with age in months directly predicting the percentage of trials ending in a comfortable position.

The inclusion of the adult comparison group in the current study indicated that on this task the oldest children were not at adult level in terms of selecting grasps for end-state-comfort. This is in line van Sweiten et al. (2010) who found that although the ability to plan movements for end-state-comfort may develop between 4-11 years and adulthood, performance is still not in line with that of skilled adult movers. However, this finding contrasts that of Thibaut and Toussaint who found that 10 year-olds were performing at the level of their adult group. A possible reason for this may simply be due to task complexity and the corresponding performance of the adult group. In the van Sweiten study 100% of adults selected grasps for end-state-comfort, in the current study 86% of movements by adults ended in end-state-comfort. It is possible that the adults in the Thibaut and Toussaint study performed at a slightly lower level. However, as no data on this group is provided by Thibault and Toussaint it is difficult to draw firm conclusions.

The current study used a categorical measurement of end-state-comfort (ending in comfort or not) but also tried to quantify comfort of the end position by using the value of comfort assigned to each end thumb position by a group of independent raters. The inclusion of this measure allowed us to consider whether a lack of group differences was due to all groups ending movements in the same degree of comfort or due to an imprecision of measurement. The quantification of comfort data demonstrated the same effects as the percentage of movements ending in end-state-comfort. This supports the conclusion that there was difference in the level of end comfort of movements made by 10-11 and 8-9 year-olds or between 6-7 year-olds and 4-5 year-olds. However, a developmental shift between the 10-11/8-9year-olds and 6-7/4-5year-olds was seen.

The end-state-comfort effect has not previously been considered in sequential movements. In an adult study Haggard (1998) showed that participants were able to plan movements on the basis of the last movement in a three movement sequence. This infers that adults do plan further ahead than just one step when planning movement. However, looking at end-state-comfort was not in the remit of the Haggard study and so whether this planning extended to executing movements on the basis of end-state-comfort was unknown. This study has shown that adults can and do plan for end-state-comfort when executing a sequence of movements. However, both the regularity of this is reduced as sequence length increases (for adults, 85% of one sequence movements end in ESC, 72% of two sequence movements and 62% of three sequence movements) as is the number of participants who consistently do this (100% of adults consistently plan for end-state-comfort for one sequence movements, 83% for two sequence movements and 75% for three sequence movements). Developmentally we see a similar pattern whereby fewer three movement sequences end in comfort compared to one movement sequences. Crucially, however, we saw no interactions between sequence length and group inferring the development of end-state-comfort/motor planning is the same for all levels of complexity.

van Sweiten et al. (2010) demonstrated that younger children favoured a minimal rotation movement over a movement ending in end-state-comfort. The current study also considered minimal rotation over end-state-comfort but found no evidence that any of the child groups favoured a no initial rotation strategy. However, when we considered the magnitude of initial rotation there was a clear difference between the groups, with the adults showing a greater degree of initial rotation compared to the 10-11 year-olds and the 10-11 year-olds showing more rotation than the other child groups. We also demonstrated a relationship between the amount of initial rotation and the percentage of movements ending in end-state-comfort whereby an individual who shows an average greater initial rotation will show a greater proportion of movements ending in comfort. The flip side of this is that those individuals who tend towards a small initial rotation will end fewer movements in comfort. This relationship supports the notion that a minimal rotation strategy may be favoured by younger children over and above ending a movement in comfort. It is worth noting that a minimal rotation strategy as seen in the van Sweiten paper described an initial rotation of 135^{o} as compared to a maximal rotation which descried an initial rotation of 225^{o}. These initial rotations are much larger than the rotations seen in the current paper and so not only have we replicated the van Sweiten finding we have also demonstrated that favouring a minimal rotation strategy occurs for much smaller initial rotations, in our study a maximal rotation was approximately 135^{o}.

This study has shown that the ability to plan for end state comfort is not fully developed at 10-11years of age, however, developmental improvements in planning for end-state-comfort are seen between 4-11 years of age. In fact, the number of movements ending in end-state-comfort could be directly predicted by age in years for all three sequence lengths. In instances where young children are ending movements in an uncomfortable position this may be due to them favouring a minimal rotation strategy at the start of the movement and opting for a grasp that is less effort at the start of the movement but which ends uncomfortably. In terms of multi-sequence movements this study has demonstrated that movements ending in a comfortable position occur less often as sequence length increases. The magnitude of this change in the number of movements ending in end-state-comfort and sequence length was the same across all age groups inferring that the ability to plan for the end of a multi-staged movement develops concurrently with the ability to plan for end-state-comfort.

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Figure 1. A. Schematic illustration of the octagon and surrounding colours, includes coding numbers that were used to code each grasp. B. Photograph of the actual set-up, the octagon shown was the largest size used. The diameters of the octagons were 13cm, 12.5cm, 10.5cm, 8 cm and 6.5cm.

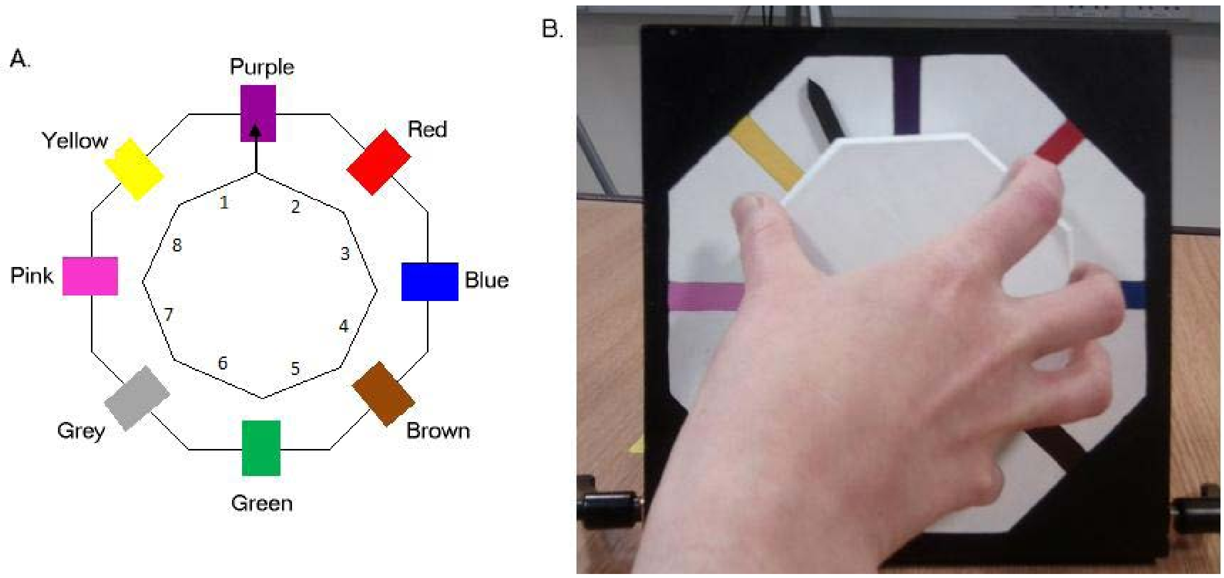

Figure 2. An illustration of the percentage of movements ending in ESC for the three age groups. Error bars represent standard error.

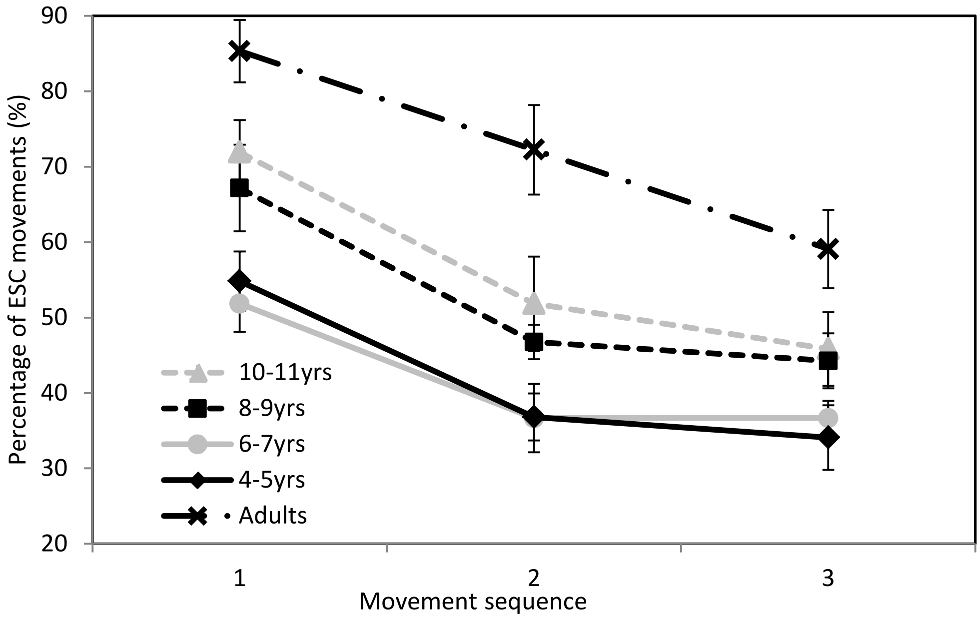

Table 1. Details of the five different age groups, including age, gender and movement assessment scores.

	Children				Adults
	4-5	6-7	8-9	10-11	
N	12	12	12	12	12
Mean Age	4 years 7 months	6 years 4 months	8 years 3 months	10 years 4 months	26 years 6 months
Gender ratio (m:f)	6:6	4:8	6:6	4:8	4:8
MABC percentile score	61.7	64	62.6	43.6	63.3
MD percentile score	53.4	59.4	58.9	43.2	63.3

Table 2. Number of participants ending the majority of movements in end-state-comfort, comfort of end position, percentage of grip changes from baseline and magnitude of initial rotation of the thumb. Data are given for all age groups and all sequence lengths. Standard deviation is given in parentheses.

		One movement sequence	Two movement sequences	Three movement sequences
Number of group members ending at least 2/3 movements in end-state-comfort	Adults	12/12	10/12	5/12
	10-11yrs	10/12	3/12	2/12
	8-9yrs	6/12	0/12	0/12
	6-7yrs	3/12	0/12	0/12
	4-5yrs	2/11	0/11	0/11
Comfort of end position	Adults	1.72 (0.35)	1.93 (0.46)	2.31 (0.35)
	10-11yrs	2.04 (0.41)	2.58 (0.54)	2.67 (0.48)
	8-9yrs	2.09 (0.25)	2.93 (0.38)	2.91 (0.27)
	6-7yrs	2.53 (0.25)	2.93 (0.38)	2.91 (0.27)
	4-5yrs	2.50 (0.54)	3.20 (0.34)	3.20 (0.55)
Proportion of initial thumb rotation trials	Adults	0.83 (0.15)	0.90 (0.24)	0.78 (0.32)
	10-11yrs	0.81 (0.22)	0.80 (0.25)	0.78 (0.20)
	8-9yrs	0.81 (0.30)	0.86 (0.15)	0.84 (0.24)
	6-7yrs	0.76 (0.28)	0.69 (0.34)	0.65 (0.32)
	4-5yrs	0.74 (0.29)	0.58 (0.33)	0.75 (0.27)
Magnitude of initial rotation of the thumb (^{o})*	Adults	81^{o} (16)	89^{o} (26)	98^{o} (29)
	10-11yrs	64^{o} (21)	73^{o} (33)	67^{o} (30)
	8-9yrs	57^{o} (16)	58^{o} (20)	51^{o} (10)
	6-7yrs	52^{o} (20)	56^{o} (21)	51^{o} (13)
	4-5yrs	58^{o} (16)	55^{o} (16)	55^{o} (15)

*This measure only includes trials were some initial thumb rotation was seen, i.e. >0.

Highlights

By 4 years children can plan a movement allowing them to end in a comfortable position

Planning for end-state-comfort develops throughout childhood

When children fail to end a movement comfortably it may be because they opt for an easier start position

Planning sequential movements develops alongside planning for single movements