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ORIGINAL ARTICLE

Representation of grasp postures and anticipatory motor planning in children

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Abstract In this study, we investigated anticipatory motor planning and the development of cognitive representation of grasp postures in children aged 7, 8, and 9 years. Overall, 9-year-old children were more likely to plan their movements to end in comfortable postures, and have distinct representational structures of certain grasp postures, compared to the 7- and 8-year old children. Additionally, the sensitivity toward comfortable end-states (end-state comfort) was related to the mental representation of certain grasp postures. Children with grasp comfort related and functionally well-structured representations were more likely to have satisfied end-state comfort in both the simple and the advanced planning condition. In contrast, end-state comfort satisfaction for the advanced planning condition was much lower for children whose cognitive representations were not structured by grasp comfort. The results of the present study support the notion that cognitive action representation plays an important role in the planning and control of grasp postures.

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Introduction

It is commonly accepted that our motor actions are planned in advance to satisfy intended action goals. For example, we might grasp a spoon with a different grip posture depending on whether we wish to place the spoon in a drawer, or whether we wish to eat from it. In the past 20 years there has been an interest in how task and experimental constraints influence our initial grasp postures during unimanual (Rosenbaum et al., 1990; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Short & Cauraugh, 1997) and bimanual object manipulation tasks (e.g., Hughes & Franz, 2008; Weigelt, Kunde, & Prinz, 2006). Typically, these studies report that individuals are more likely to grasp objects in a manner that avoids awkward final postures, even when those grasps place the limbs in highly uncomfortable initial postures. This sensitivity toward comfortable end postures (the end-state comfort effect) is taken as evidence that final grasp postures are represented in memory, and that these postures are specified before movements are initiated (Rosenbaum et al., 2001).

The tendency to avoid awkward end postures is a well-established movement constraint in healthy adult populations. However, studies that have examined the presence and development of the end-state comfort effect in children have often provided conflicting results, with some studies demonstrating similar behaviour across age groups (Adalbjornsson, Fischman, & Rudisill, 2008; Manoel & Moreira, 2005), and others demonstrating that the preference for comfortable end postures gradually improves with age (Thibaut & Toussaint, 2010; Weigelt & Schack, 2010). For example, Adalbjornsson et al. (2008) asked children to grasp an overturned cup from a table and pour water from a bucket into the cup. They found that only 27.5% of children exhibited the end-state comfort effect, and there were no

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differences between the preschool children (aged 2–3 years old), and kindergarten students (5–6 years old). In contrast to the null effects of age on initial grip selection, Weigelt and Schack (2010) found that end-state comfort increases with age. Using a bar grasping and placing task, they found that 95% of pre-school children (aged 3–5 years) used an overhand grip when this resulted in a comfortable final posture. In contrast, only 18% of the 3-year, 45% of the 4-year, and 67% of the 5-year-old children used an underhand grip when this resulted in a comfortable final posture.

Thibaut and Toussaint (2010) also investigated the developmental nature of motor planning in children aged between 4 and 10 years. In their study, children were required to grasp a horizontally positioned pencil (with a red tip on one end and a blue tip on the other) and (1) make a dot on a sheet of paper, (2) trace a line on a sheet of paper, or (3) trace a line from one location to another, without crossing the edges of the alley with the pencil. In both the "pointing-with-pencil" and "tracing-with-pencil" tasks, the tendency to satisfy end-state comfort was only observed in the 10-year-old children. Furthermore, although the data for the 4-, 6-, and 10-year-old children in these two tasks indicated that anticipatory motor planning improves with age; end-state comfort satisfaction was lower for 8-year-old children, compared to the 6-year-old children. In contrast, for the "pencil alley" task, the preference towards comfortable end-states increased as a function of age, with higher end-state comfort satisfaction for the 8-year-old, compared to the 6-year-old children.

Based on their results, Thibaut and Toussaint (2010) argued that reorganization of planning strategies during goal-directed movements occurs at the age of 8, and the observed differences between the three tasks arose as a consequence of this reorganization. They reasoned that the 8-year-old children attempted to integrate more visual cues in order to solve the task but that "*this integration is not straightforward, it leads to many errors, whereas younger children who use fewer cues have less difficulty*" (p. 128). Thus, when the constraints of the task were more defined (e.g., higher level of precision) the 8-year-old children were able to integrate visual cues and analyze the task more efficiently. In contrast, when the task did not afford a set of clearly defined constraints, 8-year-old children were unable to integrate all of the information available, resulting in a decrease in end-state comfort. Thus, the ability of children to plan for comfortable end postures is highly influenced by factors such as task context (bar transport versus grasping and pouring) and precision demands (placing versus fitting, cylindrical versus semi-cylindrical).

The emerging picture on end-state comfort development is that the preference for comfortable end postures gradually increases as a function of sensory-motor development. However, the question arises whether the insensitivity toward comfortable end-states in younger children occurs because they are not capable of anticipating future events, or whether they are unable to distinguish between initial grasp postures that result in comfortable or uncomfortable end postures. The present study sought to examine this issue, and had two primary aims. The first aim was to examine the cognitive representations for certain grasp postures in children aged 7, 8, and 9 years of age. The second aim was to investigate whether these cognitive representations develop in a similar time course as the sensitivity toward comfortable end postures.

The cognitive representation of grasp postures was evaluated using the Structural Dimensional Analysis-Motoric (SDA-M, Schack, in press; Schack & Mechsner, 2006). The SDA-M procedure allows for a psychometric analysis of the relational structures in a given set of concepts, and has been used in a number of studies addressing complex motor action (Schack & Mechsner, 2006; Weigelt, Ahlmeyer, Lex, & Schack, 2011), manual action (Schack & Ritter, 2009) and rehabilitative tasks (Braun et al., 2007). The results of these studies typically demonstrate that the cognitive representation of voluntary movements in experts are characterized by well-integrated networks of basic action concepts (BAC's), while novices or stroke patients show unstructured patterns (e.g., Blaesing, Schack, & Brugger, 2009; Braun et al., 2007; Schack & Mechsner, 2006; Weigelt et al., 2011). For example, Schack and Mechsner (2006) examined the cognitive representation of motor skills (i.e., the tennis serve) in long-term memory in non-tennis players, novice tennis players, and expert tennis players. The long-term memory structure in expert tennis players revealed a hierarchically clustered representational structure, with well-integrated networks (i.e., basic action concepts) that each corresponded to functionally meaningful sub-movements. In contrast, the cognitive representations in non-tennis and novice tennis players were less structured, and exhibited greater between-subjects variability, compared to their expert counterparts.

In the present experiment, the cognitive representation of grasp postures was evaluated using a splitting procedure, in which children were shown a pair of pictures, and asked if the pictures were similar or not. The pictures depicted an object (a hammer, a glass, or a pair of scissors), that was grasped with either a comfortable or uncomfortable grip. Thus, it was possible for children to cluster the pictures according to tool (e.g., cluster the three hammers together, the three glasses together, and the scissors together), cluster the pictures according to grip type (e.g., cluster all the tools held with a comfortable posture together, and cluster all the tools held with an uncomfortable posture), or not cluster the pictures in a structured manner. We hypothesized that the cognitive representation of grasp postures would develop as a function of age. That is, the representational structures in

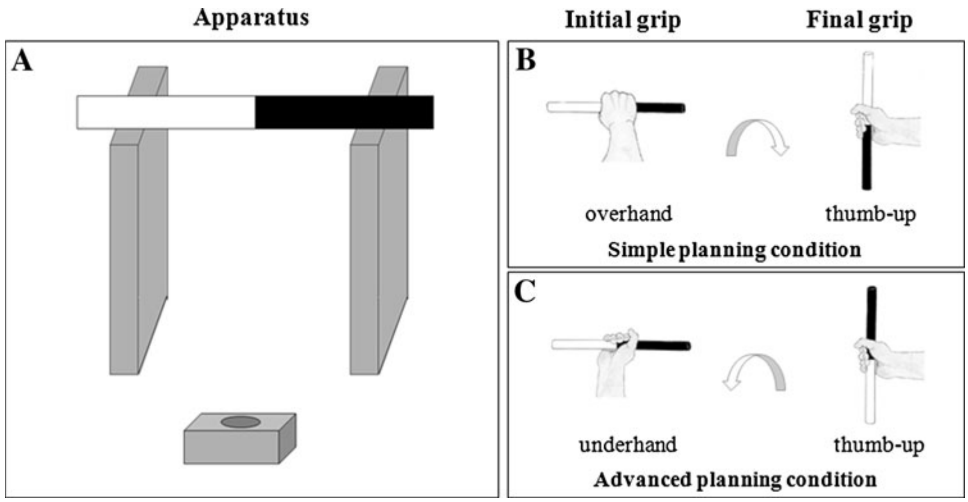

Fig. 1 The apparatus used in the grasping and placing task consisted of a cradle, a wooden bar, and a target. One end of the bar was painted *black*, and the other end was painted *white*. **a** Depicts the bar positioned so that the black end of the bar is facing the right. **b** and **c** illustrate representative initial and final grasp postures for the simple and advanced planning condition, respectively. The *arrow* serves to indicate the direction in which the bar is to be rotated

9-year-old children would be hierarchically clustered, with comfortable grasp postures clustered separately from uncomfortable postures. In contrast, the cognitive representations in 7-year-old children would be less structured, indicating that they do not possess the ability to distinguish comfortable postures from uncomfortable postures.

Based on the equivocal findings on end-state comfort sensitivity over the developmental spectrum, we also examined the sensitivity toward end-state comfort during a bar transport task. Based on previous literature (Thibaut & Toussaint, 2010), we hypothesized that the sensitivity toward comfortable end postures would increase as a function of sensory-motor development, but reach levels observed in healthy adult populations by the age of 9.

We also investigated whether the ability to plan for comfortable postures (bar transport task) was related to the ability to separate uncomfortable grasp postures from comfortable grasp postures (SDA-M task). We hypothesized that end-state comfort satisfaction should be higher for children with distinct grasp posture representations, compared to children with less structured representations. Such a finding would support the notion that the insensitivity toward comfortable end-states is due to an inability to distinguish between initial grasp postures that result in comfortable or uncomfortable end postures, rather than a general inability of children to anticipate future events.

Methods

Participants

Thirty-six primary school children aged 7 years (6 girls, 6 boys), 8 years (8 girls, 4 boys), and 9 years (7 girls, 5 boys) participated in the experiment. The mean age of the 7-year-olds was 86.2 months (SD = 2.5), 99.1 months (SD = 4.3) for the 8-year-olds, and 111.2 months (SD = 3.2) for the 9-year-olds. Based on the Edinburgh Handedness Inventory (Oldfield, 1971), all children were deemed to be right-handed (mean laterality index = 89.2, SD = 10.9). Informed consent of children's parents was obtained prior to participation in the experiment. The research was approved by the local school authorities and the institutional review board.

Bar transport task

Apparatus The apparatus is depicted in Fig. 1a. The wooden bar (length: 22 cm, diameter: 2 cm) was painted black on one end and white on the other end, and rested on a horizontal support. The space between both supports was 20 cm and the bar was raised 25 cm above the table. The target was a cube with a round hole in the centre (2.5 cm diameter), which was placed 10 cm in front of the supports (cf. Weigelt & Schack, 2010). The apparatus was placed on a table, which was height-adjusted so that the child's breast coincided with the wooden bar. The starting position for each participant was marked by placing a piece of tape on the floor (10 cm length, 2 cm in width) 90 cm in front of the bar. Grasp postures were recorded using a video camera (Panasonic NV-DX 100) placed 3 m from the right horizontal plane of the apparatus.

Task and procedure The task was to pick up the bar with the right hand using either an *overhand* (palm-down) or an *underhand* (palm-down) grip, and to insert either the black or the white end into the target hole of the cube. For half of the trials the black end was oriented to the right (Fig. 1a), and for the other half of the trials the black end was oriented to the left. Thus, when the black end of the bar was oriented to the right, comfortable end postures were achieved by grasping the bar with an overhand grasp when the black end was to be inserted to the target (Fig. 1b), and with an underhand grasp when the white end was to be inserted to the target (Fig. 1c). In contrast, when the black end of the bar was oriented to the left, comfortable end postures were achieved by grasping the bar with an underhand grasp when the black end was to be inserted to the target, and with an overhand grasp when the white end of the bar was to be inserted to the target.

At the start of each trial, the child stood behind the starting line with their hands by their sides. After receiving verbal instructions about which end of the bar to insert into the target hole, the child walked up to the apparatus, picked up the bar and inserted the required end into the target hole. The children were instructed to grasp the bar using a full power grip and to hold the bar at the target location for 5 s to emphasize the end of the movement. After the movement was completed, the child placed the bar back onto the supports, and walked back to the starting position.

Children performed two trials in each of the four conditions (i.e. each end had to be inserted twice for each start orientation of the bar). Thus, there was a total of eight trials consisting of the 2 start-orientation (black end to the right, black end to the left), 2 end-orientation (black end inserted to the target, white end inserted to the target) × 2 trial[1] (trial 1, trial 2). The start orientation of the bar was counterbalanced across children, and the individual trials were randomized. Initial grasp (i.e. overhand vs. underhand grip) and the final hand posture (i.e. thumb-up vs. thumb-down) were recorded by the experimenter on a predefined score sheet. The experiment took approximately 15 min per child, and was conducted without speed pressure.

Data analysis We defined children as satisfying end-state comfort if they grasped the object with a hand posture that resulted in a comfort posture at the end of the movement in at least 3 of the 4 trials (Adalbjornsson et al., 2008; Weigelt & Schack, 2010). Differences in initial grasp behaviour across the three age groups were examined using one-way Chi-square tests for the simple and advanced planning conditions separately.

Structural dimensional analysis-Motoric task

Apparatus and stimulus Children sat on a height-adjustable chair in front of the table, with the computer monitor 57 cm away. The computer monitor (43 cm) was situated coincident with the midline. The stimuli consisted of nine images that depicted a hand holding a hammer, a glass, or a pair of scissors, with either a comfortable or an uncomfortable grip. Based on an initial pilot study with 8 adults, three of the nine pictures (U1, U2, and U3 in Fig. 2) were always classified as uncomfortable. In contrast, three were always classified as comfortable (1, 3, and 5 in Fig. 2). The three remaining pictures (2, 4, and 6 in Fig. 2) were clustered with the comfortable pictures. However, there was a clear distinction between the two sets of comfortable pictures. Specifically, pictures 1, 3, and 5 (comfortable grips) were clustered together with lower Euclidean distances than pictures 2, 4, and 6 (ambiguous grips). Based on the results of this pilot study, the three ambiguous grips were included in the experiment in order to increase the demands of the task, and allow for the emergence of more fine-grained differences between children.

Task and procedure At the start of the SDA-M task, the children listened to the following cover story: "*There are two families who live next to each other. The name of one family is Sauber (German translation for someone who is organized or clean) and the name of the other family is Wusel (German translation for someone who is chaotic). The families don't like each other very much, because they are so different and they behave differently around the household. While the Sauber's perform all of their daily living activities perfectly and grasp all objects in their house in a very comfortable manner, the members of the Wusel family perform all these activities in an opposite manner and grasp objects uncomfortably. In the following, I will show you some pictures of grasping activities in the Wusel and Sauber families and I want you to tell me if the pictures belong to the same family or not.*"

After hearing the story, the children were asked if they understood the task, and had any questions answered by the experimenter. The mental representation of grasp postures in long-term memory was determined using a split procedure (first step of SDA-M). Each picture of a grasp posture was offered as an anchor (i.e., a reference picture located at the top of the list) to which participants classified the remaining *N*-1 pictures as similar or non-similar to the anchoring picture (pictures from the same family: yes or no). For example, in the upper half of the computer screen was a picture of a hand holding a hammer with a comfortable grasp posture (anchor) and in the lower half of the screen was a picture of hand holding a glass with an uncomfortable grasp posture (reference). The child was asked to compare the two images and respond verbally whether they thought the two pictures came from the same family or not, and the experimenter recorded the answer on a pre-specified score sheet. The children then judged the similarity of the remaining concepts to the anchor picture. After all judgments were made with that anchor picture, another concept occupied the anchor position, and all other concepts were compared to this anchor concept.

[1] Based on previous research demonstrating that grasping behaviour in the bar transport task is relatively consistent between trials (e.g., Thibaut and Toussaint, 2010; Weigelt and Schack, 2010) and that behaviour should be similar irrespective of initial bar orientation (black end oriented to the right, black end oriented to the left), we used two trials per condition to test for end-state comfort sensitivity.

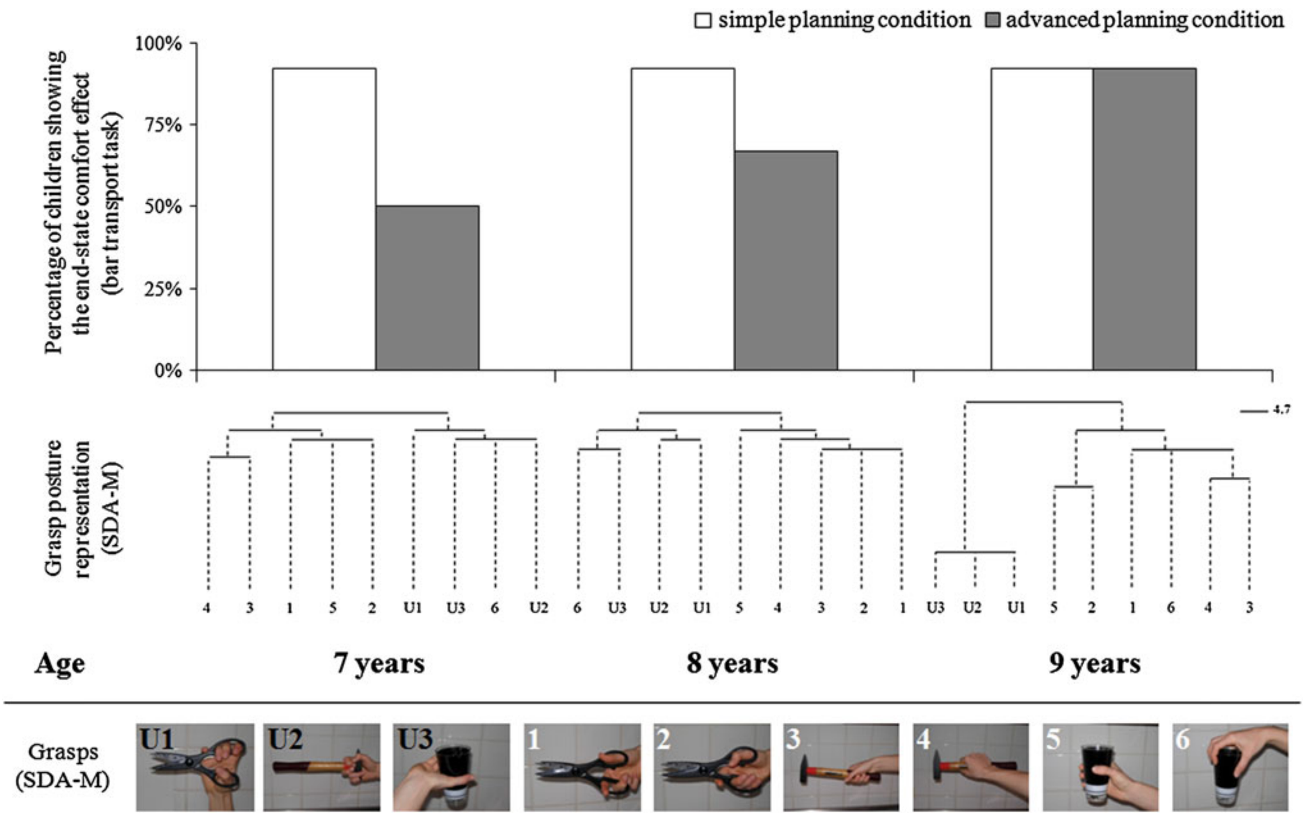

Fig. 2 *Top panel*: end-state comfort satisfaction (proportion of children) in the bar transport task for the simple (*white bars*) and advanced planning condition (*grey bars*). *Middle panel*: the representational structures for comfortable and uncomfortable grips for the 7-year old children, the 8-year old children and the 9-year old children. Depicted are the averaged group data based on the SDA-M analysis. *Bottom panel*: images of the stimuli used in the SDA-M task. *Pictures 1–6* depict comfortable grasp postures, and pictures *U1–U3* depict uncomfortable grasp postures

Data analysis The (SDA-M) method consisted of four steps.[2] In the first step the participant judged the similarity of all pictures (Basic Action Concept's [BAC's]) with one another (described in full in the previous section), which produced positive or negative partial quantities between each BAC (family Wusel or family Sauber in relation to the anchoring picture). Because this anchor role was assigned to each BAC in succession, a total of 9 decision trees were formed. The nodes of these decision trees contained the resulting subsets and the borders between subsets were positive (indicating that the element was judged as belonging to the standard) or negative (indicating that the element was judged as not belonging to the standard). To obtain a measure of the distance between the successively judged elements and the standard (with interval scaling), algebraic sums were computed over the subsets located on one branch of the decision tree. These sum scores were then z transformed.

In the second step of the SDA-M, the individual partitions between clusters were determined by means of a hierarchical cluster analysis which formed individual cluster solutions (depicted as a dendrogram). In the third step of the SDA-M, the feature dimensions of these individual cluster solutions were determined by transforming the *Z*-matrix into a correlation matrix. This factor matrix formed the final solution of the individual SDA-M as a concept quantity. Finally, in the fourth step, a within- and between-group comparison of the cluster solutions was performed by determining the structural invariance (λ) between cluster solutions. An invariance measure of $\lambda < \lambda_{crit} = 0.68$ was used to determine significance (Schack, in press), which corresponds to an alpha level of $p = 0.05$.

Subsequent to the invariance analysis, specific differences between the representational structures at each age group were examined using the Rand Index (Rand, 1971). The Rand Index ranks the similarity between two clusters on a scale from 0 to 1, where the value "0" indicates that the two data clusters have no similarities and the value "1" indicates that the data clusters are identical. We then examined whether the ability to separate uncomfortable grasp postures from comfortable grasp postures differed across the three age groups using one dimensional Chi-square analysis.

Finally, the representational structures at each age group were compared to an ideal representational structure.

[2] See a detailed description of the SDA-M in the electronic supplementary material.

The dendrogram of an ideal structure has one distinct cluster for comfortable (pictures 1, 3, 5 in Fig. 2) and ambiguous (pictures 2, 4, 6 in Fig. 2) postures, and another distinct cluster for uncomfortable postures (pictures U1, U2, U3 in Fig. 2).

Results

Bar transport task

Figure 2 shows the percentage of children that performed the bar transport task in a manner consistent with the end-state comfort effect for the overhand grip and the underhand grip averaged across the four trials in each condition separated by age. First inspection of the data revealed that 92% of the children satisfied end-state comfort when an overhand grip resulted in a comfortable end posture. In contrast, only 83% of participants used an underhand grip when this resulted in a comfortable end posture.

With respect to the three age groups tested, equally high end-state comfort satisfaction values (92%, see Fig. 2, simple planning condition) were observed when an overhand grip posture was required to satisfy end-state comfort. In contrast, age related differences were observed when an underhand grip was required to finish the movement in a comfortable posture (see Fig. 2, advanced planning condition). 50% of the 7-year-old children, 67% of the 8-year-old children and 92% of the 9-year-old children showed the end-state comfort effect in that condition. Because of the observed differences across simple and advanced planning conditions, we examined the data for the simple and advanced planning condition using separate one dimensional Chi-square tests. Analysis indicated that grasp behaviour was identical across the three age groups during the simple planning condition (χ^2 (2) = 0.0, $p < 1.0$). In contrast, there were significant differences in grasping behaviour between the age groups in the advanced planning condition, χ^2 (2) = 42.2, $p < 0.001$.

Structural dimensional analysis: Motoric task

Representational structures (dendrograms) for comfortable and uncomfortable grasp postures for the 7-, 8-, and 9-year-old children are displayed in Fig. 2. The memory structures of 7- and 8-year-old children did not show any distinct clustering of comfortable and uncomfortable grasp postures. The branches of the dendrogram were all below the critical value of $d_{crit} = 4.7$ (based on a significance level of 5%). In contrast, the memory structures of the 9-year-old children revealed two distinct clusters ($d = 5.0$, $p < 0.05$) with one cluster with only 3 items (all being examples of uncomfortable grasp postures, see the grasps/pictures with black numbers in Fig. 2) and a cluster including 6 items (all objects held with a comfortable grasp). Thus, 9-year-old children clustered comfortable and uncomfortable grasps differently, with uncomfortable grasps represented very close together in long-term memory ($d = 1.1$).

Analysis revealed that the representational structures of the 7-year-old children and the 8-year-old children were identical (rand index = 1.0). Additionally, rand index values when comparing the clusters of the 7-year-olds with the clusters of the 9-year-olds, and the clusters of the 8-year-olds with those of the 9-year-olds, indicated that the clusters shared similar features, but were not identical to one another (both rand index values = 0.78). Closer inspection of the data revealed that 33% of the 7-year-old children, 58% of the 8-year-old children and 75% of the 9-year-old children were able to separate uncomfortable grasp postures (pictures U1, U2, U3 in Fig. 2) from comfortable grasp postures (pictures 1, 3, 7 in Fig. 2). Chi-square analysis revealed that the number of children who clustered by grasp comfort increased as a function of age, $\chi^2(2) = 36.1$, $p < 0.001$.

Lastly, when the representational structures at each age group were compared to an ideal representational structure, analysis indicated that the representational structures of the 7-year-old and 8-year-old children shared similar features to the ideal structure (both rand indices = 0.78). By comparison, the representational structures of the 9-year-old children were identical to the ideal structure (rand index = 1.0).

The relationship between mental representation of grasp postures and motor planning

To investigate the relationship between the mental representation of grasp postures (SDA-M task) and motor planning (bar transport task), we separated the children (regardless of age) into two groups. One group of children ($n = 20$), were able to separate uncomfortable grasp postures (pictures U1, U2, U3 in Fig. 2) from comfortable grasp postures (pictures 1, 3, 7 in Fig. 2), and were classified as children who clustered by grasp comfort.[3] The second group of children ($n = 16$) did not cluster according to grasp comfort (comfortable vs. uncomfortable), and were classified as children who did not cluster by grasp comfort.

We then compared the structural representation data with end-state comfort behaviour in both the simple and advanced planning condition (Fig. 3). All of the children who clustered by grasp comfort ($n = 20$) performed the bar transport task in a manner consistent with end-state comfort in the simple as well as in the advanced planning condition.

[3] Although the majority of children clustered the pictures with ambiguous grasps (pictures 2, 4, 6) with the comfortable grasps (pictures 1, 3, 5), they were not used in the classification of group affiliation.

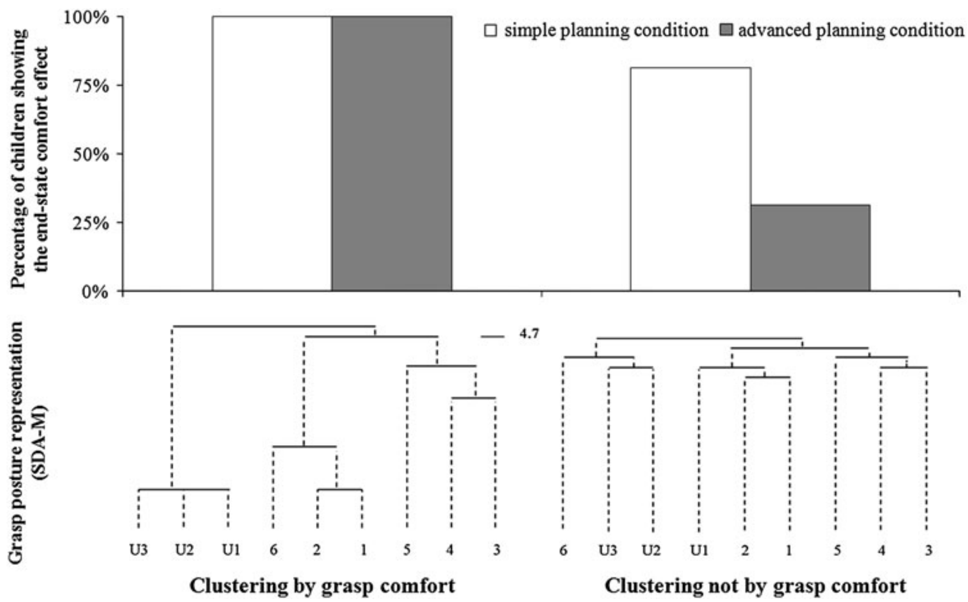

Fig. 3 Results of the bar transport task when participants were grouped according to their clustering in the SDA-M task. *Top panel*: percentage of children who satisfied end-state comfort in the bar transport task for the simple (*white bars*) and advanced planning condition (*grey bars*). *Bottom panel*: mental representation of grasp postures based on the results of the SDA-M task. There were distinct clusters for uncomfortable, compared to comfortable and ambiguous, grasp postures for children who clustered by grasp comfort (shown on the *left*). In contrast, there were no clear clusters between grasp postures for children who did not cluster by grasp comfort (shown on the *right*)

In contrast, end-state satisfaction for the children who did not cluster by grasp comfort was influenced by planning condition. Specifically, 81.3% (13 out of 16) of children satisfied end-state comfort in the simple planning condition. However, this value dropped to 31.3% (5 out of 16) children in the advanced planning condition. Chi-square analyses confirmed the difference between the two groups to be significant for the simple planning condition, $\chi^2(1) = 3.98$, $p = 0.046$, as well as for the advanced planning condition, $\chi^2(1) = 19.25$, $p < 0.001$.

Discussion

The primary purpose of the present study was to examine the cognitive representation for certain grasp postures in children aged 7-, 8-, and 9-years of age. Overall, 9-year-old children showed distinct clusters for comfortable and uncomfortable grasps, which were identical to an ideal representational structure. In contrast, the clusters for comfortable and uncomfortable grasps in 7- and 8-year-old children were less stable and organized than that of the 9-year-olds, and differed from an ideal representational structure. Thus, the results of the SDA-M experiment indicate that the cognitive representation of certain grasp postures unfolds over the developmental spectrum, but that the ability to distinguish between comfortable and uncomfortable grasp postures is not fully matured until the age of 9.

A secondary purpose of the present experiment was to examine children's sensitivity toward end-state comfort during a unimanual grasping and placing task. In general, end-state comfort satisfaction increased across the three age groups. However, in comparison to the "pointing-with-pencil" task of Thibaut and Toussaint (2010), we observed higher overall end-state comfort satisfaction values across all three age groups. We attribute this discrepancy to precision differences in the two experiments. In the Thibaut and Toussaint (2010) study, children used a pencil to make a dot on a 6 cm diameter piece of paper. In contrast, we asked children to fit a 1.5 cm object into a 2.5 diameter cm hole, which required a higher level of precision at the end of the task. Furthermore, our task involved *fitting* the object into a target hole, which requires greater precision at the end of the movement than making a dot on a piece of paper (see Hughes et al., 2011a, b for a similar argument). Thus, it is likely that the higher level of precision at the end of the movement influenced the sensitivity toward comfortable end-postures.

To get an idea of how end-state comfort planning develops across a large age range, we compared our results to those of Weigelt and Schack (2010) who examined motor planning in children aged between 3 and 5-years using the same unimanual grasping and placing task. In both experiments, children satisfied end-state comfort when an overhand grasp posture was required to end comfortably (simple planning condition). However, when an underhand grasp posture was required to end comfortably (advanced planning condition), end-state comfort increased as a function of age. Specifically, Weigelt and Schack (2010) found that 18% of 3-year-olds, 45% of 4-year-olds, and 67% of 5-year-olds used an underhand grasp posture when required. Likewise, we found that 50% of 7-year-olds, 67% of 8-year-olds, and 92% of 9-year-olds satisfied end-state comfort for this condition. Thus, it appears that the ability to plan for comfortable end postures increases over the developmental spectrum and reaches levels typically observed in adult populations by the age of 9.

The data also revealed that the ability to plan for comfortable postures was related to the ability to separate uncomfortable grasp postures from comfortable grasp postures. When the children were separated into groups based on the ability to cluster grasp postures by comfort, we found that all of the children who clustered by grasp comfort performed the bar transport task in a manner consistent with end-state comfort in the simple as well as in the advanced planning condition. In contrast, end-state satisfaction for the children who did not cluster by grasp comfort was influenced by planning condition. Specifically, although 81.3% (13 out of 16) of children satisfied end-state comfort in the simple planning condition, this dropped to 31.3% (5 out of 16) children in the advanced planning condition.

Why were the children who did not cluster by grasp comfort unable to reliably satisfy end-state comfort in the advanced planning condition? One possibility is that these children do not have the cognitive capabilities to plan their movements in anticipation of future events. However, this interpretation seems unlikely given the large number of studies demonstrating that children and infants are capable of prospective motor control (Claxton et al., 2003; Kuhtz-Buschbeck et al. 1998; von Hofsten, 1993). For example, infants under 2 years of age will adjust their grip size depending on the size of the target (von Hofsten & Ronnqvist, 1988), will adjust their speed of reaching for a ball depending on whether they intend to throw it into a tub or fit it down a tube (Claxton et al., 2003), and when reaching for an object they anticipate contact with (von Hofsten, 1993).

Another hypothesis is that the inability of some children to plan for comfortable end-postures results from competition between the goal-directed and the habitual system. As stated in the introduction, the goal-directed system selects actions depending upon both current and future task requirements (Johnson-Frey et al., 2004; Rosenbaum et al., 1990), which influence grasp posture planning (as illustrated by the end-state comfort effect) and movement execution (Hughes et al., 2011a). However, there is evidence that grasp posture planning is also influenced by the habitual system. For example, a number of researchers have also shown that the mere observation of an object can automatically activate information regarding how to use and manipulate the object, even when people have no intention of acting on the object (Grafton et al., 1997; Grezes & Decety, 2002; Tucker & Ellis, 1998). Further, it appears that action planning and execution is influenced by both the goal-directed and the habitual selection systems, and is mediated by factors such as working memory (Weigelt et al., 2009), object orientation, object type, the environment, and the internal state of the individual (Herbort & Butz, 2011).

In line with this perspective, we hypothesize that both the goal-directed and habitual system play a critical role in anticipatory motor planning, and is, at least partially, mediated by the children's cognitive representation structures in long-term memory. During the simple planning condition, grasp preferences of the habitual system and the goal-directed system both call for the adoption of an initial overhand grip, thereby facilitating the selection of the appropriate grasp posture. However, during the advanced planning condition grasp preferences of the habitual system and the goal-directed system call for different initial postures (overhand grip and underhand grip, respectively). The conflict resolution between possible initial grasp postures is further influenced by the children's cognitive representation of grasp postures.

This hypothesis is supported by the results of the grasping and placing task. When the grasp posture predicted by the habitual system and goal-directed system were identical (i.e., simple planning condition), end-state comfort satisfaction was similar between the three age groups, and corresponded to values commonly observed in adult populations (e.g., Rosenbaum et al., 1990). However, when the grasp posture predicted by the habitual and goal-directed systems were different (advanced planning condition), only the children with developed cognitive representations were able to anticipate future grasp postures, and mediate the bias toward overhand grasp postures driven by the habitual system. In comparison, children with less developed cognitive representations were less able to anticipate future grasp postures, and as such the habitual system served to mediate grasp posture planning.

The results of the bar transport task and cognitive representation task support the inference that well structured cognitive representations aid in the development of grasp posture planning. However, due to the cross-sectional design of the current experiment, we cannot rule out the possibilities that the sheer experience of manipulating various objects leads to more structured mental representations, or that the increase in both end-state comfort and the cognitive representation of grasp postures is driven by an, as yet unknown, third variable.[4] Thus, it would certainly be worthwhile to examine the development of anticipatory

[4] We thank an anonymous reviewer for pointing out this possibility.

planning and mental representations using a longitudinal or cross-sequential research design. Researchers should also utilize questionnaires or interview techniques in future studies, as the relationship between cognitive representations and anticipatory planning might be mediated by cognitive, physical, family, and cultural factors.

In conclusion, 9-year-old children were more likely to plan their movements to end in comfortable postures, and have distinct representational structures of certain grasp postures, compared to the 7- and 8-year old children. However, the ability to plan for comfortable postures was related to the ability to separate uncomfortable grasp postures from comfortable grasp postures. Children who clustered by grip comfort satisfied end-state comfort in the simple as well as in the advanced planning condition, whereas end-state comfort satisfaction in children who did not cluster by grasp comfort was significantly lower for the advanced than for the simple planning condition. The results of the present study support the notion that the cognitive representation plays an important role in the planning of grasp postures.

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