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Effects of visual and visual-haptic perception of material rigidity on reaching and grasping in the course of development

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A B S T R A C T

The development of material property perception for grasping objects is not well explored during early childhood. Therefore, we investigated infants', 3-year-old children's, and adults' unimanual grasping behavior and reaching kinematics for objects of different rigidity using a 3D motion capture system. In Experiment 1, 11-month-old infants and for purposes of comparison adults, and in Experiment 2, 3-year old children were encouraged to lift relatively heavy objects with one of two handles differing in rigidity after visual (Condition 1) and visual-haptic exploration (Condition 2). Experiment 1 revealed that 11-months-olds, after visual object exploration, showed no significant material preference, and thus did not consider the material to facilitate grasping. After visual-haptic object exploration and when grasping the contralateral handles, infants showed an unexpected preference for the soft handles, which were harder to use to lift the object. In contrast, adults generally grasped the rigid handle exploiting their knowledge about efficient and functional grasping in both conditions. Reaching kinematics were barely affected by rigidity, but rather by condition and age. Experiment 2 revealed that 3-year-olds no longer exhibit a preference for grasping soft handles, but still no adult-like preference for rigid handles in both conditions. This suggests that material rigidity plays a minor role in infants' grasping behavior when only visual material information is available. Also, 3-year-olds seem to be on an intermediate level in the development from (1) preferring the pleasant sensation of a soft fabric, to (2) preferring the efficient rigid handle.

1. Introduction

Reaching and grasping movements are purposeful goal-directed actions that require the planning and prediction of movements, as well as the perception of object properties (Von Hofsten & Lindhagen, 1979). From the very beginning of life the grasping movements of infants are prospective and goal-directed (Bruner & Koslowski, 1972; Von Hofsten, 1980, 2004), and at the end of the first year of life they are adjusted to object size, distance, shape, texture, weight and spatial orientation (Barrett et al., 2008; Gottfried & Rose, 1980; Libertus et al., 2013; Molina & Jouen, 2003; Newell et al., 1989; Newman et al., 2001; Paulus & Hauf, 2011; Ransburg et al., 2017; Ruff, 1984; Siddiqui, 1995). However, much less is known about the effect of material rigidity on reaching and grasping in infants.

From adult research, we know that different material properties like elasticity, viscosity and rigidity are inferred from visual motion and haptic cues, obtained via specific exploration strategies (Kawabe et al., 2015; Paulun et al., 2015, 2017; Schmidt et al., 2017; Van Assen et al., 2018; Zöller et al., 2019). For instance, visual motion cues include information about object deformations or shape changes, whereas haptic cues combine tactile and kinesthetic information. Both sensory input channels provide important information for differentiating between material properties (e.g., a compliant material will be easily deformed) and thus for successful grasping. Although there is an almost infinite number of combinations in terms of spacing and timing of arm and finger movements, adults show very stereotypical and repeatable

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reaching kinematics. Different object properties influence these typical patterns in a very specific way, so that a characteristic kinematic pattern is generated for each object (Klein et al., 2020; Paulun et al., 2016). Here, we test how visual and haptic information contributes to infants' differentiation and recognition of material rigidity and whether they are integrated to realize efficient and functional grasping movements.

1.1. Visual and haptic perception of object properties

Efficient goal-directed movements require the integration of visual and haptic feedback (Stone & Gonzalez, 2015). Vision is essential for recognizing objects, locating grasp targets, preparing proper anticipatory grasp configuration, accurate endpoint positioning and avoiding obstacles while grasping. Vision also allows us to estimate a variety of object properties even without touching them (Adelson, 2001; Fleming, 2014, 2017). For example, object shape and size can be inferred from static visual cues (Heller, 1982; Manyam, 1986), as can optical surface properties such as glossiness, which might indicate friction (Adams et al., 2016; Beck & Prazdny, 1981; Fleming et al., 2003). In contrast, mechanical object properties such as mass, elasticity, rigidity, hardness and slipperiness benefit from indirect dynamic visual information (Masuda et al., 2011, 2013, 2015; Paulun et al., 2017; Schmidt et al., 2017; Todd & Warren, 1982; Warren et al., 1987), such as observing object deformations during object motion or watching someone interact with the object (Berger et al., 2005; Cellini et al., 2013; Drewing et al., 2009; Kawabe et al., 2015). As a consequence, detection of object rigidity can be difficult, especially for infants, who are less experienced with objects and their properties.

Haptics, in contrast to vision, is mainly used to identify, explore and manipulate objects. It is constantly used in everyday life, often unconsciously, for instance when reaching for an object in a bag, closing a zipper or pressing the keys of an instrument (Lederman & Klatzky, 1987). Haptic impressions arise in actively moving persons, whereby information from the body's own movement, e.g. about position and orientation of body parts and joints, as well as information from physical contact with an object or subject, such as weight, compliance and thermal conductivity, is processed (Cellini et al., 2013; Drewing et al., 2009; Grunwald, 2012). The compliance of an object determines the way in which an object is deformed by the hand and therefore plays a particularly important role in haptic differentiation and identification (Bergmann Tiest & Kappers, 2006; Hollins et al., 2000). Also, haptic judgements about softness are more reliable and consistent than visual judgements (Cellini et al., 2013; Drewing et al., 2009), which underlines that object compliance is more easily perceived in haptics compared to vision.

1.2. Early perception of object rigidity in vision

Few developmental studies have investigated how infants integrate visual information about objects of different rigidity into grasping movements. Imura et al. (2015) demonstrated infants' ability to derive the rigidity of object surfaces from visual motion information at the end of their first year of life. Videos of a stick, penetrating a hemisphere with different velocity profiles, indicated either a soft or a crusty hemisphere surface. 11- to 12-month-old infants showed a novelty preference for soft stimuli after familiarization with crusty stimuli and vice versa. In comparison, 9- to 10-month-olds only showed a looking time preference for soft stimuli, suggesting an earlier development of visual sensitivity towards soft surfaces as compared with crusty ones. This finding was not due to differences in low-level properties (e.g. stick velocity) but to material properties, as shown in a control study (Imura et al., 2015). Still, it remains unclear whether infants could use this rigidity information when grasping an object. This was investigated by Barrett et al. (2008) who showed 5- to 15-month-old infants only visual information about four balls, two of which were made of hard plastic and two of flexible rubber. Material behavior was not demonstrated before grasping, limiting infants' visual information about object rigidity. However, the visual surface appearance differed significantly, potentially signaling differences in object rigidity. Results showed cleaner grasps for rigid than for flexible balls in all age groups, i.e., with more corrections of grasp position on the flexible balls. Also, infants used fewer fingers when grasping the flexible balls. In conclusion, both studies (Barrett et al., 2008; Imura et al., 2015) suggest that infants visually distinguish material rigidity at an early age. Also, adaptation of grasping movements might be better for rigid objects. However, it remains unclear to what extent these findings were based on visual perception of object rigidity per se, versus other cues such as surface appearance or texture.

1.3. Early perception of object rigidity in touch

Rigidity can be easily detected through haptic exploration by applying pressure to object surfaces, as for example by squeezing (Bushnell & Boudreau, 1991; Drewing, 2014; Lederman et al., 1996; Lederman & Klatzky, 1987). Even very young infants show specific oral and manual exploration patterns when presented with rigid and nonrigid objects and surfaces (Bourgeois et al., 2005; Gibson & Walker, 1984; Palmer, 1989). Fewer studies focused on infants' reaching and grasping behavior for objects of different rigidity. Corbetta and Snapp-Childs (2009) encouraged 6- to 9-month-old infants to grasp soft pompoms and rigid balls of two different sizes. While the large rigid ball required bimanual grasping, the small rigid ball, as well as the large soft pompon, allowed uni-manual grasping. Infants in all age groups showed an individual, intrinsic motor tendency towards either one- or two-handed reaching and grasping, independent of object size. Reaching and grasping behavior was not systematically affected by object material even after several visual and haptic explorations. The authors concluded that new motor responses require a lot of practice before they are consistently maintained and reproduced by the infants.

Two other studies used the same objects to investigate 4- to 6-month-old infants' rigidity perception when grasping. On the one hand, Rocha et al. (2006) found neither differences in grasping frequencies nor in kinematic parameters (e.g. mean velocity, movement units, trajectory straightness) for soft and rigid balls, while kinematic parameters were affected by infant age and object size. On the other hand, De Campos et al. (2011) found higher grasping frequencies for soft wool pompons compared to rigid polystyrene balls, from which the authors concluded that softness promotes young infants' grasping.

However, it has to be noted that in these reaching and grasping studies (Barrett et al., 2008; Corbetta & Snapp-Childs, 2009; De Campos et al., 2011; Rocha et al., 2006), material was confounded with the surface texture and shape of the objects. While rigid balls had a smooth surface, wool pompons offered many small bulges to hold on to, rendering conclusions about the perception of rigidity unfeasible. Also, the studies did not distinguish between the first grasping trial, when infants had merely seen the object, and later trials, when they had haptic experience from touching the object. Therefore, the role of visual versus visual-haptic perception of object rigidity for grasping is still open.

1.4. Early perception of object rigidity in vision and touch

To the best of our knowledge, no previous study investigated the separate roles of visual and haptic perception of object rigidity for infants' reaching and grasping. However, some studies suggest that haptics and vision are not yet well integrated in the first year of life (Catherwood, 1993; Corbetta et al., 2000; Corbetta & Snapp-Childs, 2009; Gottfried et al., 1977; Gottfried & Rose, 1980; Stack & Tsonis, 1999). For example, vision prevented infants from recognizing the shape of an object during its manipulation (Gottfried et al., 1978; Rose et al., 1979), and haptic perception of texture was not facilitated by vision, although it increased attention during exploration (Stack & Tsonis, 1999). Nevertheless, another study by Paulus and Hauf (2011) suggests that infants integrate visual and haptic information about object weight at around 11 months. Boxes of different weights and colors were provided with either visual or visual-haptic weight information. After manually exploring the boxes, 9- and 11-month-olds remembered their weight and preferentially grasped the lighter box. In another experiment, infants haptically explored a soft and compressible platform as well as the boxes. Then, the boxes rested on the soft platform, which was only compressed by the heavier box. Infants still preferred grasping the lighter box. In a final experiment, infants did not haptically explore the boxes and were just shown the boxes resting on the platform. As a result, 11-months-olds did reach for the lighter box while 9-month-olds did not, showing that only for 11-months-olds visual information was sufficient to infer object weight. Here, we want to investigate whether these separate contributions of visual and haptic information also hold for object rigidity.

1.5. *Aims of the study*

To sum up the previous work on this topic: Some infant studies on the role of visual and haptic perception for grasping addressed object properties such as texture, shape, and size. Other studies that focused on the role of object rigidity for grasping dealt with the role of visual aspects, while others dealt with the role of haptics. To the best of our knowledge, no study has examined both aspects in combination to investigate how young children adjust their reaching and grasping behavior when perceiving object rigidity only from vision compared to from visual and haptic exploration. Moreover, while dynamic visual information about object deformations has been shown to be a central feature of rigidity perception in adults, this has not been featured so prominently in infant studies to date. Therefore, the goal of the present study was to investigate the influence of dynamic visual and haptic object information on uni-manual reaching movements to objects of different rigidity in young children. In particular, young children's grasping frequencies and kinematic reaching parameters were analyzed using a quantitative 3D motion capture system. We aimed to test whether children understand that and how the object usage is determined by object rigidity. To answer this question, we created relatively heavy stimulus objects (still liftable by an infant) which could be grasped and lifted by using one of two handles attached to the objects. The handles were visually very similar but differed in rigidity: one handle was rigid and the other one was compliant (note: throughout we use the terms compliance and softness interchangeably). Using one single object with two handles of different rigidity allowed us to present both handle materials simultaneously and have the children choose one of the handles for lifting the object. As the soft handles deformed under the object's weight, grasping and lifting the objects was most functional and efficient when using the rigid rather than soft handles. In order to substantiate this assumption, we tested a group of adults who can be expected to grasp the objects in the most efficient way. In Study 1, we used the adult data for a comparison of the reaching and grasping behavior with 11-month-old infants. Previous studies found this age group to be able to infer object rigidity from visual information and use this information for reaching tasks (Barrett et al., 2008; Imura et al., 2015). In Study 2 we investigated the behavior of 3-year-olds in the same task. Berger et al. (2005) let 16-month-old infants cross narrow and wide bridges while choosing between a rigid wooden handrail and a flexible fabric or latex handrail. The infants used rigid handrails more frequently, demonstrating their ability to use object rigidity information for efficient motor behavior. Thus, we also expected young children in our study to prefer grasping and lifting the objects by the rigid handle, although probably to a lesser extent than adults.

To investigate the relative importance of visual and haptic object information on reaching and grasping, participants were asked to use the handles to lift the objects either after visual inspection of the handles or after additional haptic exploration. We expected high action efficiency and thus higher grasping frequencies towards rigid handles in young children in the visual-haptic condition compared to the visual condition (cf. Paulus & Hauf, 2011). In addition, we compared young children's and adults' movement trajectories while reaching for soft and rigid object handles to map out developmental changes in reaching movements. For object properties such as size, orientation, and shape, grasping kinematics have already been well studied (De Campos et al., 2011; McCarty & Ashmead, 1999; Newell et al., 1993; Ransburg et al., 2017; Siddiqui, 1995; Von Hofsten & Fazel-Zandy, 1984; Von Hofsten & Rönnqvist, 1988), but few studies have addressed kinematics during reaching for objects of different rigidity (Rocha et al., 2006). We investigated parameters related to efficient grasping, expecting higher precision with increasing efficiency. In particular, we expected reaching trajectories to become straighter and faster with fewer corrections for rigid compared to soft handles. This assumption is based on the fact that the goal of an action is explicit in the case of rigid materials, whereas soft materials allow more variability in grasping and hand positioning, as it adapts to the hand during grasping. For example, an increased grip force leads to a stronger deformation of the material, which must be included in action planning. This means that soft and flexible objects afford more detailed grasp planning and produce more frequent repositioning and manual exploration before grasping compared to rigid objects (Barrett et al., 2008).

As reaching trajectories are faster and more precise with more sensory input (McCarty & Ashmead, 1999), and as action planning improves with increasing experience, we expected straighter and faster trajectories in the visual-haptic compared to the visual condition. In addition, we predicted changes in reaching kinematics with increasing age as a result of improving abilities in responding to object demands during development (Konczak & Dichgans, 1997). More specifically, we predicted straighter and faster reaching with velocity profiles increasingly approaching typical adult trajectories.

Study 1

2. *Method*

2.1. *Participants*

Twenty-four 11-month-old infants and twenty-five adults participated in Study 1. Infants were recruited by obtaining birth records from local municipal councils and neighboring communities and contacting parents by mail. Adults were undergraduate students at the University of Giessen. The group of 11-month-olds consisted of 14 male and 10 female infants ($M = 351.25$ days; $SD = 7.20$; range = 340–364 days). Data of four infants were not included in the data analysis because of lack of cooperation ($n = 1$), crying ($n = 1$) or lack of interest in the test objects ($n = 2$). For the adult sample, we first tested a group of 8 male and 10 female adults ($M = 20.84$ years; $SD = 2.15$; range = 18–26). This group showed a clear preference for grasping the rigid handle (will be described in detail in Section 3.1), thus confirming our assumption about the role of rigid handles for more functional grasping in our task. However, as a consequence, these adults produced only very few grasping trials towards soft materials ($n = 9$), rendering a statistical comparison of kinematic parameters between grasping towards soft and rigid material difficult. Therefore, we tested an additional group of 2 male and 5 female adults ($M = 20.86$, $SD = 2.41$; range = 18–25).

The current study was conducted in accordance with the German Psychological Society (DGPs) research ethics guidelines. The Office of Research Ethics at the University of Giessen approved the experimental procedure and the informed consent protocol. Written informed consent was obtained from adult participants and from infants' parents prior to their participation in the study.

2.2. *Stimuli and apparatus*

The two objects shown in Fig. 1 served as test objects A and B.

Both test objects consisted of a large wooden sphere (10 cm in diameter) with two handles (3 cm in diameter, 14 cm in length). The

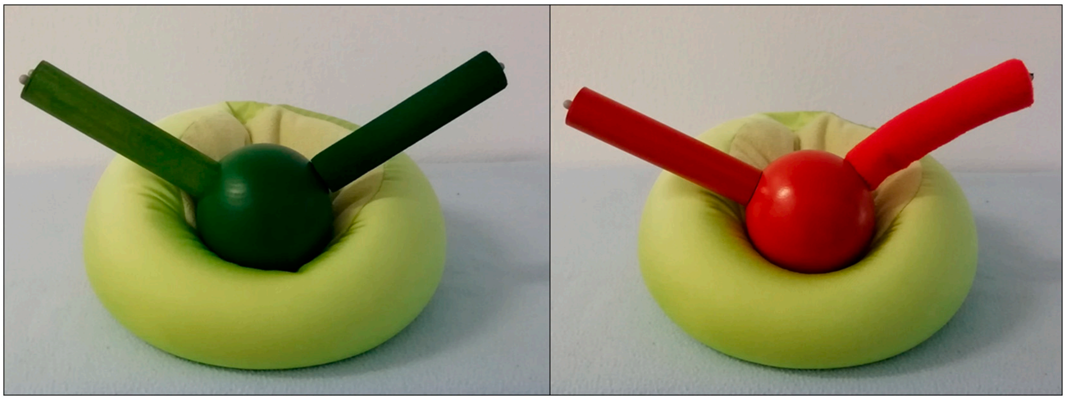

Fig. 1. Both test objects are set on a compressible pillow to demonstrate their heavy weight. Test object A was colored green and its handles were made of wood (left handle) and foam material (right handle). Test object B was colored red and its handles were made of hard plastic (left handle) and fabric filled with cotton (right handle). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

entire object weighted 500 g which is a liftable weight for 11-month-olds (see Paulus & Hauf, 2011). Piloting before the actual experiment confirmed that 11-months could lift the objects easily with one hand. In order to visually illustrate the considerable weight of objects, we placed them on a soft pillow which they compressed. This was shown to be a feasible procedure to provide children at that age with visual information about the weight of objects (Hauf et al., 2012). As relatively large objects in everyday life, the two handles offered a high grasping affordance. The handles allowed grasping and lifting the objects despite their size and weight. They were mounted on the ball so that the ends pointed upwards diagonally. This was to make the overhand grip, which is typically used by 11-month-old infants (McCarty et al., 2001), comfortable on both sides of the object. The two handles of each object were made from different materials: one from a rigid and the other from a soft material. The rigid object handles allowed the objects to be lifted easily, while the soft handles deformed significantly under the weight of the objects. As a result, the objects tilted to the side and were more difficult to lift. To minimize the influence of shape or surface appearance, the handle materials were visually very similar to each other and painted in the same color. Test object A was colored green and its handles were made of wood and foam material. Test object B was colored red and its handles were made of hard plastic and fabric filled with cotton (see Fig. 1). We chose different colors and materials for the two test objects to alleviate fatigue effects.

Reaching movements were recorded with a 3D optical marker-based motion capture system (VICON, Oxford, England). Six infrared cameras (Bonita and T-series) tracked the motion of small reflective markers (6 mm in diameter) with a sampling rate of 50 Hz. The experimenter attached markers on the nail of thumb, index finger and on the inner and outer wrist of the participant's grasping hand. Further markers were attached to the endings of the stimuli handles and to the table. Grasping movements were additionally recorded with a commercially available 2D video camera from a bird's eye perspective. Data of both camera types were synchronized.

2.3. Procedure and design

The procedure consisted of a preparation phase and a test phase. In the preparation phase, participants sat across from the experimenter at a table. Infants sat on a parent's lap. Parents were instructed to hold their child and to remain silent and neutral during testing. To familiarize the child with the setting and the experimenter, there was a short period of free play with various toys. The experimenter also used this period to identify the child's preferred grasping hand: she offered a toy to the child and observed with which hand the child grasped it. In addition, the parents were asked whether they had observed a preferred grasping hand in their child. If the parents' statements agreed with the experimenter's observation, this hand was determined as the preferred hand. If they did not agree, two more grasping attempts were observed and the hand with which the child grasped more often was determined as the preferred hand for the experiment. After selecting one hand as the preferred hand, all trials were performed with this hand (right $n = 16$, left $n = 4$). The experimenter attached the markers to the participant's preferred grasping hand and continued the phase of free play until the child was feeling comfortable and the test phase started.

In the test phase, each of the two test objects was first presented in a visual condition, followed by a visual-haptic condition. In the visual condition, the experimenter drew the child's attention to test object A. Starting hand position was determined by a paper hand glued to the tabletop to provide better recognition of the movement start in the kinematic analysis and to keep the grasping movement constant. At the beginning of each trial parents held their child's preferred hand at the starting position and the non-preferred hand on the child's lap. In the visual condition, rigidity was indicated visually by tapping on the handles and pushing them down with a stick one after another (Fig. 2). In response, the soft handle moved and deformed while the rigid handle stayed put but produced knocking sounds. Considering that 11-month-olds were shown to distinguish materials of different rigidity based on visual motion information only (Imura et al., 2015) and even younger infants used visual information about object rigidity in a reaching task (Barrett et al., 2008), we assumed that 11-month-olds in our study would also be able to infer handle rigidity from the presented visual information.

After this visual demonstration, the experimenter slid the object towards the child and stopped just at the edge of the infant's reaching space to encourage one-handed grasping, while parents released their child's reaching hand, but not the non-preferred hand. As soon as the child had reached for one handle and lifted the object, the experimenter cheered and took the object away. The visual condition was repeated with test object B. If the infant did not reach for the object the trial was repeated once, but only if the child had not touched the object yet, in order to exclude any haptic information. Immediately after the visual condition, the visual-haptic condition followed, consisting of manual object exploration and three grasping trials for each object. For this, the experimenter put the test object A directly into the hands of the child, encouraged him or her to manually explore the object for 30 s (haptic and visual information). After manual exploration, three grasping trials were carried out with the same procedure as in the visual condition. The manual exploration and three grasping trials for the visual-haptic condition were then repeated with test object B. If the infant showed no grasping attempt in a trial, it was repeated once. Regarding both conditions, the spatial orientation (left, right) of the handle materials (soft, rigid) as well as the presentation sequence of the objects (A, B) were counterbalanced across infants. For each child, the rigid handle of object A as well as object B was presented two times on the left side and two

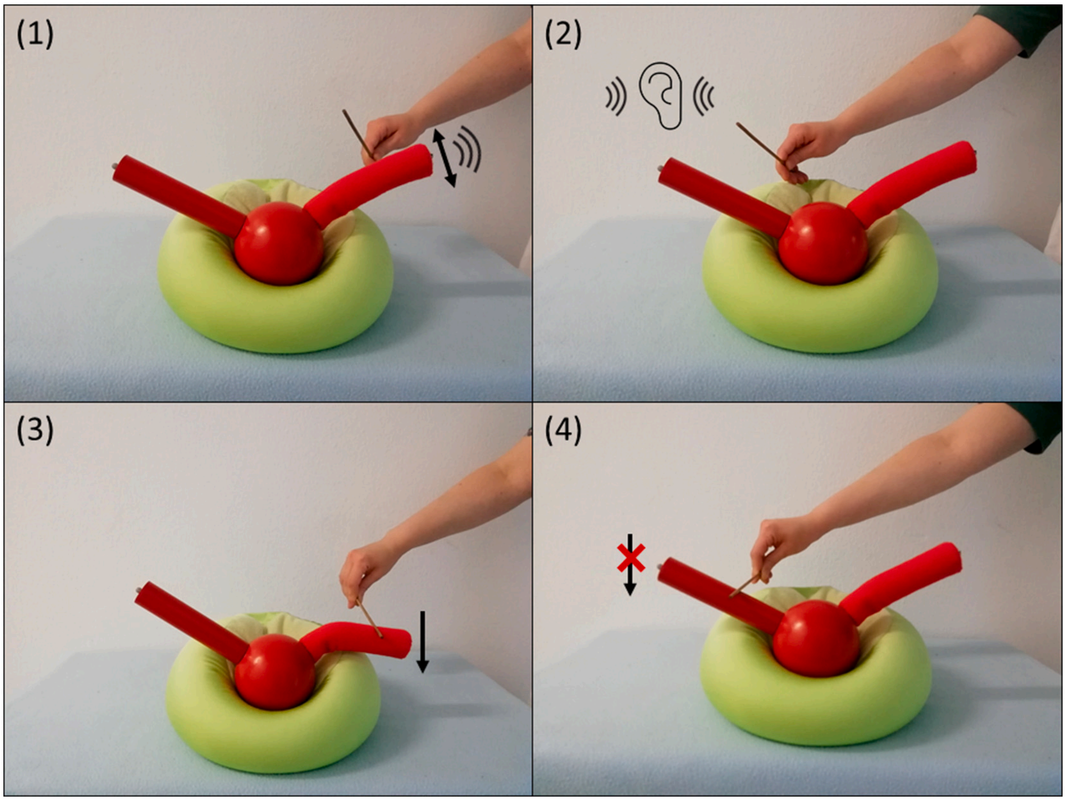

Fig. 2. Material rigidity of the handles was visually demonstrated by tapping both handles one after another (upper panels) and then by pushing them down with a stick one after another (lower panels). Tapping produced a wobbling motion of the soft handle (1) and a knocking sound of the rigid handle (2). Pressing down the handles deformed the soft handle (3) but not the rigid handle (4).

times on the right side in randomized order over both conditions. Half of the children received the red object first; the other half received the green object first. The experimenter always used both hands when touching the objects and only grasped them at the center ball to avoid any cues about object properties or expected grasping behavior. The hand-object distance in the start position differed depending on the arm length between the participants, because the object was always slid so close to the participant that it was within reaching distance. By sliding the object centrally towards the child's grasping hand, it was possible to maintain equal distance between the hand's starting position and both object handles. Still, infants had to cross the midline when grasping the contralateral handle relative to the grasping hand. Crossing the midline successfully occurs from about 3 to 4.5 months in children's grasping development (Provine & Westermann, 1979), which is why we did not consider contralateral grasping as a restriction. After testing, infants received a small toy and a certificate.

The testing of adults was kept as similar as possible to the 11-month-olds'. Adults were instructed verbally to grasp the object at one of the two handles by using only one hand. Also, adults were instructed to lift the object and then place it on a target point on the table in front of them. The target point was a paper dot glued to the table that was on a straight line between the grasping hand and the middle of the test object. The additional group of adults (mentioned above) was only tested to assess their kinematics regarding their reaching for rigid compared to soft handles. This group of adults had the same preparation phase as the other adult group. However, in the testing phase, they were only asked to alternately grasp the ipsilateral and the contralateral handle with orientation of soft and rigid handles counterbalanced across all trials. The handle to be grasped was therefore predetermined on each trial. As described above, the first trial per object was in the visual condition, followed by an exploration phase and three trials in the visual-haptic condition. After testing, all adult participants were rewarded with course credits.

2.4. Measures

Grasping frequencies were evaluated from the data recorded by the 2D camera, and kinematic parameters from the data recorded by the 3D cameras. Because infants were not instructed to place the object on the table as adults were, only trials in which they showed an obvious grasping movement with an attempt to lift the object were included in the analyses. This was not the case when an infant showed no interest in the object and did not perform a grasping and lifting movement (25 trials), only pointed at the object, pushed it away or grasped it bimanually (21 trials), when the infants did not look at the object during grasping (9 trials), or when the parents interacted with their child (7 trials). This resulted in evaluable trials of 16 children. The average number of missing trials was $M = 0.62$ trials per infant ($SD = 0.72$) in the visual condition and $M = 1.25$ trials per infant ($SD = 1.18$) in the visual-haptic condition. However, at least one visual and three visual-haptic trials were analyzable for all children. For the adults, all trials could be used for the analysis.

In order to evaluate whether infants and adults differentiated between soft and rigid materials when they grasped the objects, we analyzed their grasping frequencies for the different handles and assigned them to three response categories: preference for rigid handles (rigid handles were grasped most frequently), preference for soft handles (soft handles were grasped most frequently), or no preference (rigid and soft handles were grasped equally frequently). For infants who removed the attached markers several times from their hands and for whom the experimenter did not succeed in directing their attention to the objects, the markers were removed and the experiment was finished without markers. In this case, only data for the frequency analysis were obtained, but not for kinematic analyses. Nexus 2.2.3 (VICON, Oxford, England) was used for preprocessing the kinematic data. In case of missing marker recognition, e.g. when markers were obscured by the object, the mother's hand, or by the child's own movements, the gaps were filled and thus reconstructed retrospectively. All further kinematic analyses were carried out with MATLAB 2019a (MathWorks, Natick, MA, USA). First, raw data were filtered with a first-order Butterworth low-pass filter with a cut-off frequency of 8 Hz. Then, the kinematic parameters were calculated as follows: (1) *Relative reaching duration*: Time from movement onset to the end of the reaching movement when the handle was touched. Movement onset was defined as the point when the velocity of the wrist marker exceeded a threshold of 30 mm/s (Brouwer et al., 2009). At the end of the reaching movement, the velocity of wrist markers approaches zero, with a short peak when the fingers touch the object (Ransburg et al., 2017). This peak was defined as the end of the reaching movement. Since the arm lengths differed greatly between the age groups, we calculated relative reaching durations. As in our experiment, the arm length corresponded to the distance of the hand to the object in the starting position, we defined relative reaching duration as the ratio between the absolute reaching duration and the object-hand-distance at movement start. (2) *Mean reaching velocity*: The velocity *v(t)* is the first derivative of the distance *s(t)* after the time *t*. Therefore, the mean velocity was calculated as the mean of the distance divided by the absolute duration of the reaching movement of the wrist markers. In general, the mean reaching velocity is related to the difficulty of the task and increases with decreasing task difficulty. (*3*) *Straightness index (SI): SI* reflects the straightness of the reaching trajectory, calculated by the quotient of the trajectory length and the distance between start and end position of the wrist markers. As SI increases, the straightness of the trajectory decreases. A perfectly straight movement would result in SI = 1.00 (Rocha et al., 2006; Thelen et al., 1996). (*4*) *Movement units (MU)*: The number of MUs is a measure of how often acceleration and deceleration occurs during a movement. It was calculated as the count of velocity peaks that exceed 20% of the maximum resultant hand velocity in each trial (Konczak & Dichgans, 1997). A typical velocity curve of an adult is bell-shaped and therefore has exactly one MU (Blischke, 2010). Differences in kinematic parameters were tested by using mixed measures ANOVAs with the between-subject factor age group and the within-subjects factors material and condition (2 × 2 × 2). In all tests, the level of significance was set to $p <$ .05. Statistical analyses were conducted in IBM SPSS Statistics 26.

3. Results

3.1. Grasping frequencies and grasping sides

All 11-month-olds and adults consistently used overhand grasps with the palm facing down. As they had the choice between grasping the ipsilateral or the contralateral handle relative to the grasping hand, we tested whether the handle side influenced their grasping frequencies. We conducted a Fisher's exact test, which revealed a significant interaction between age and preferred grasping side ($p < .01$). Most adults equally often grasped the ipsilateral and contralateral handles (67%; 12 of $n = 18$; Fig. 3), while three quarters of the 11-months-olds grasped the ipsilateral handle more frequently (75%; 12 of $n = 16$).

Next, we tested if the grasping categories were affected by handle material (soft, rigid) and condition (visual, visual-haptic). For adults, Fisher's exact test revealed a significant relation between condition and preferred material ($p < .01$). The majority of the adults preferred to grasp the rigid handles over the soft handles in both the visual (61.1%; 11 of $n = 18$) and the visual-haptic condition (100%; 18 of n = 18) (Fig. 4). Seven adults (38.9%) grasped the soft and rigid handle equally often in the visual condition. None of the adults preferred the soft handle over the rigid handle in either condition (0%). This is consistent with our assumption that lifting the heavy objects is more functional and efficient when using the rigid handle instead of the soft and flexible one. Moreover, the additional haptic information seems to reinforce this behavior.

Since the 11-months-olds showed a same-side bias, we conducted separate frequency analyses for the ipsilateral and contralateral grasps,

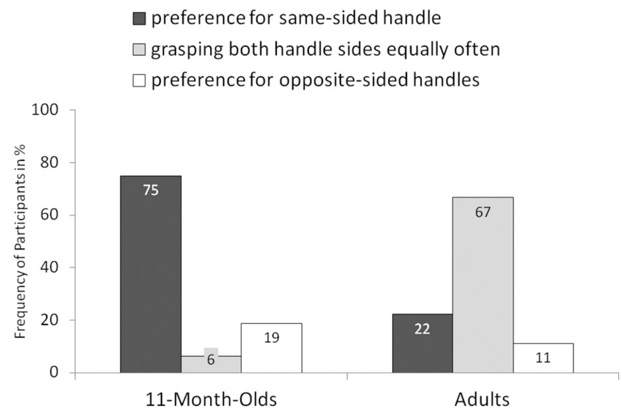

Fig. 3. Percentages of adults' ($n = 18$) and 11-month-olds' (n = 16) grasping behavior are shown for the ipsilateral and contralateral handles.

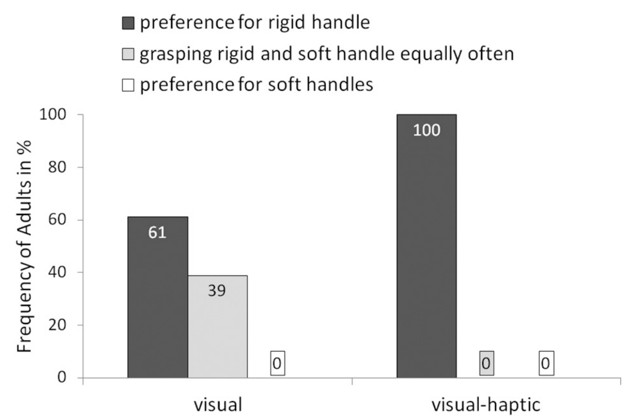

Fig. 4. Percentages of adults' grasping behavior are shown in the visual and visual-haptic condition (n = 18).

also taking the conditions (visual and visual-haptic) into account. Fisher's exact test revealed no significant relation between condition and preferred material when grasping the ipsilateral handles ($p = .28$). The frequency distribution of the grasping categories showed, though, that the majority of infants preferably grasped the soft handles in the visual (40%; 4 of $n = 10$) and visual-haptic condition (60%; 9 of $n = 15$; Fig. 5). Thus, infants did not show efficient and functional grasping as adults and as expected, but a tendency to prefer the soft handles in both conditions.

When grasping the contralateral handles in the visual condition,

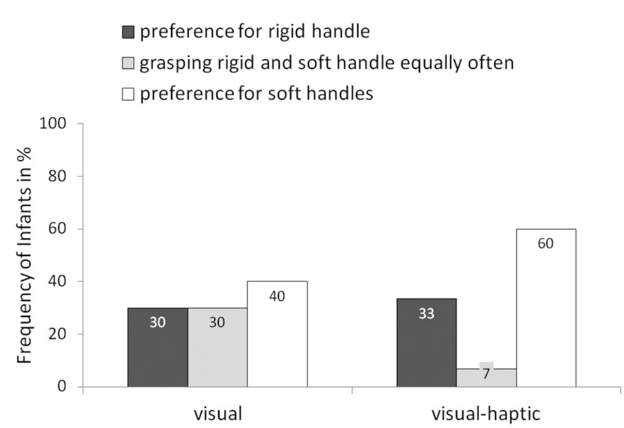

Fig. 5. Percentages of infants' grasping categories in the visual (n = 10) and visual-haptic condition (n = 15) for ipsilateral grasps.

three infants preferred the soft handles and two infants preferred the rigid handles. Due to the very small number of infants in this condition ($n = 5$), no statistical analysis was calculated. However, in the visual-haptic condition, the majority of infants preferred the soft handles in contralateral grasps (88.9%; 8 of $n = 9$). One infant (11%) grasped the rigid and soft handles equally often whereas no infant preferred the rigid handle (Fig. 6). This was supported by a binomial test, revealing a significant difference between 11-month-olds' grasping probability and chance (50%; $p < .05$). This demonstrates a significant grasping preference for soft handles in the visual-haptic condition for contralateral grasps.

In summary, adults, who showed no grasping side-bias, demonstrated a preference for rigid handles in the visual and visual-haptic conditions. 11-month-olds, however, showed a bias to grasp the ipsilateral handles. Regarding these ipsilateral grasps, they tended to prefer the soft over the rigid handles in the visual and the visual-haptic condition. When infants grasped the contralateral handles, they significantly preferred the soft handles, but only in the visual-haptic condition.

3.2. Kinematic analysis

All kinematic measurements of the two adult samples were tested for comparability. Results did not reveal any significant statistical differences (all p values $> .05$). Therefore, we summarized the kinematic parameters of the two adult samples, allowing us to perform analyses for grasps to rigid ($n = 162$) as well as soft handles ($n = 38$).

We compared the kinematic parameters when infants and adults reached for soft and rigid handles in the visual and visual-haptic conditions. As the majority of infants did not reach for both grasping sides instead of *t*-tests for dependent samples, we conducted t-tests for independent samples. They revealed no significant differences for any kinematic parameter between the ipsilateral and the contralateral handles in both age groups (all $p > .05$). Thus, we averaged the kinematic variables across the grasping sides in all following analyses.

For each reaching parameter, a mixed measures ANOVA with between-subject factor age group and within-subject factors material and condition was calculated. For the SI, a significant main effect of material was found, $F(1, 281) = 5.15$, $p < .05$, $\eta_p^2 = 0.01$, indicating straighter movement trajectories for rigid than for soft materials. The main effect of condition was also significant, $F(1, 281) = 73.23$, $p < .01$, $\eta_p^2 = 0.13$, with straighter trajectories in the visual-haptic compared to the visual condition. Another significant main effect was found for age group, $F(1, 281) = 57.97$, $p < .01$, $\eta_p^2 = 0.10$, revealing higher straightness in adults than in infants. The analysis also showed a significant interaction for age group and condition, $F(1, 281) = 105.48$, $p < .01$, $\eta_p^2 = 0.18$. An increase in straightness was observed in the infants' movements from the visual ($M = 1.26$, $SD = 0.09$) to the visual-haptic condition ($M = 1.09$, $SD = 0.05$) while there was no difference in the adults' movement straightness between conditions. A significant interaction for material and age group, $F(1, 281) = 30.36$, $p < .01$, $\eta_p^2 = 0.05$, showed that material rigidity affected the movement straightness of infants and adults differently. Infants showed slightly straighter trajectories for soft handle materials ($M = 1.11$, $SD = 0.07$) compared to rigid materials ($M = 1.16$, $SD = 0.12$). Adults instead revealed slightly straighter trajectories for rigid materials ($M = 1.09$, $SD = 0.05$) compared to soft materials ($M = 1.13$, $SD = 0.08$). The interaction for material and condition was also significant, $F(1, 281) = 18.80$, $p < .01$, $\eta_p^2 = 0.03$. In the visual condition, there was no difference in straightness between both materials, whereas in the visual-haptic condition, trajectories were straighter in grasps to rigid compared to soft materials.

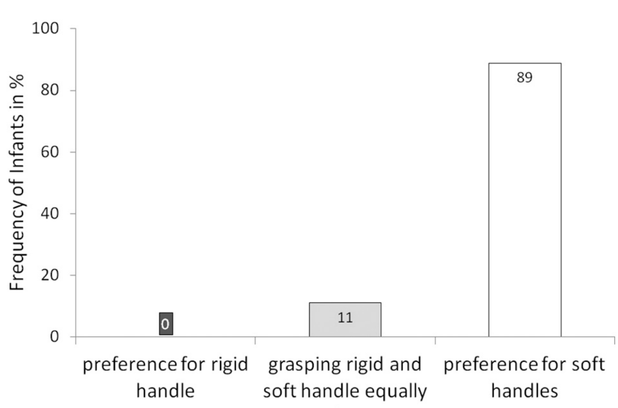

Fig. 6. Percentages of infants' grasping behavior are shown for the visual-haptic condition for trials where they grasped the contralateral handles (n = 9).

For mean reaching velocity, a significant main effect of age group was found, $F(1, 252) = 17.43$, $p < .01$, $\eta_p^2 = 0.06$, with a higher mean reaching velocity in adults ($M = 45.27$ cm/s, $SD = 11.33$ cm/s) compared to infants ($M = 35.38$ cm/s, $SD = 9.58$ cm/s).

For relative reaching duration, we found a significant main effect of condition, $F(1, 252) = 8.03$, $p < .01$, $\eta_p^2 = 0.03$, with higher relative reaching durations in the visual ($M = 28.55$ ms/cm, $SD = 5.04$ ms/cm) compared to the visual-haptic condition ($M = 27.63$ ms/cm, $SD = 5.59$ ms/cm). Also, there was a significant main effect of age group, $F(1, 252) = 32.15$, $p < .01$, $\eta_p^2 = 0.11$, with shorter relative reaching durations in adults ($M = 26.92$ ms/cm, $SD = 5.05$ ms/cm) compared to infants ($M = 30.33$ ms/cm, $SD = 5.84$ ms/cm).

For movement units, a significant main effect of condition was found, $F(1, 281) = 46.64$, $p < .01$, $\eta_p^2 = 0.08$, with fewer MUs in the visual-haptic ($M = 1.34$, $SD = 0.64$) compared to the visual condition ($M = 1.75$, $SD = 1.08$). Another significant main effect of age was found, $F(1, 281) = 222.07$, $p < .01$, $\eta_p^2 = 0.38$, with fewer MUs in adults ($M = 1.11$, $SD = 0.36$) compared to infants ($M = 2.21$, $SD = 0.98$). The main effects were qualified by a significant interaction for age group and condition, $F(1, 281) = 33.43$, $p < .01$, $\eta_p^2 = 0.06$. Infants showed a greater decrease in the number of MUs from the visual ($M = 3.00$, $SD = 0.98$) to the visual-haptic condition ($M = 1.85$, $SD = 0.81$) compared to adults (visual: $M = 1.18$, $SD = 0.49$, visual-haptic: $M = 1.08$, $SD = 0.30$).

Among all reaching parameters, no other main effect and no interaction between age group, material and condition were significant ($p > .05$). In summary, infants' trajectories were straighter for soft handles, while adults' trajectories were straighter for rigid handles. This suggests more efficient reaching for the preferred handle material in both age groups. Furthermore, in the visual-haptic condition, trajectories were more precise as they were characterized by fewer MUs and shorter relative reaching durations compared to the visual condition. Also, infants' reaching movements were straighter with additional haptic information (compared to visual information only), while adults did not show a difference in SI between the conditions. Adults showed an improved ability in responding to object demands as indicated by higher mean velocities, shorter relative reaching durations, and fewer movement units compared to 11-month-old infants.

Fig. 7 shows example movement trajectories of one adult and one infant. All trials for each participant are visualized, with dashed lines representing trajectories in the visual condition and solid lines representing trajectories in the visual-haptic condition. The figure shows that adults' trajectories contain typical aspects of reaching movements, straight and bell-shaped with one MU. Also, intra-individual differences are low, which is reflected in similar curve shapes across trials. In contrast, infants' trajectories have multiple acceleration and deceleration peaks, resulting in more than one MU per trial. Also, intra-individual differences are high, with spatio-temporal courses varying considerably.

4. Discussion

The aim of the present study was to investigate the influence of visual and haptic information on uni-manual reaching and grasping movements towards objects of different rigidity in infancy compared to

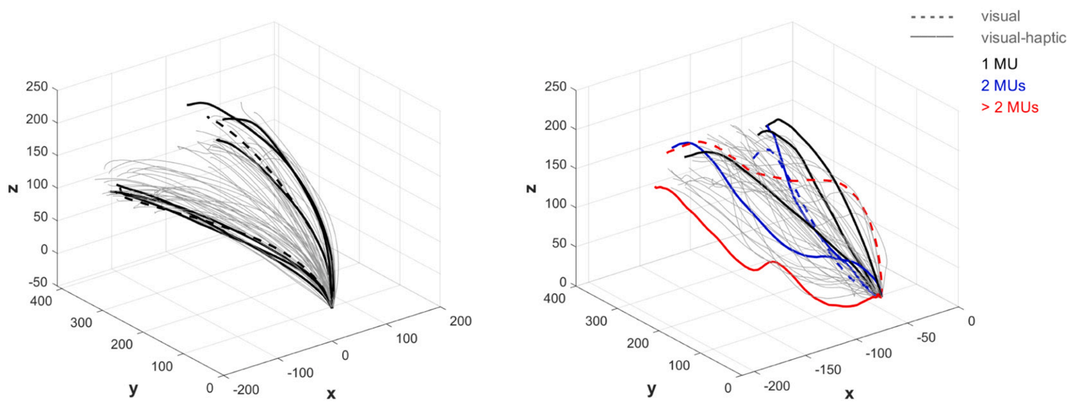

Fig. 7. An example selection of reaching trajectories of adults (left) and infants (right). Highlighted are all trajectories from one adult and one infant. Colors indicate the count of MUs: black 1 MU, blue 2 MUs, red >2 MUs. Line type represents the condition: - - visual condition, – visual-haptic condition. Trajectories have been shifted to the same starting point for better comparison. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adults.

First, we found a strong bias in infants to grasp the ipsilateral handles. This bias dominated infants' grasping behavior and was not influenced by handle material, neither in the visual nor in the visual-haptic condition. On the one hand, one could assume that infants' strong preference to grasp the ipsilateral handles is the result of a preference to apply an overhand radial grip (over an overhand ulnar grip), which has been observed in tool use studies in this age group (Keen et al., 2014; McCarty et al., 1999, 2001). In the overhand radial grip, the thumb points towards the action end of a tool, for example the bowl of a spoon, with the palm facing down (Keen et al., 2014). More specifically, McCarty et al. (1999) found that, when a spoons' handle pointed to the right, 9- and 14-month-old infants (who preferably used their right hand for grasping) consistently used a comfortable radial overhand grip. More interestingly, however, when the handle was directed to the left, the infants still used a comfortable radial overhand grip, using their non-preferred left hand. However, in about half of the trials, they also showed an uncomfortable ulnar overhand grip with the thumb pointing away from the spoon bowl with their preferred right hand, although this grip is inefficient, making it difficult to guide food to the mouth. In summary, although the infants seemed to have a preexisting tendency for a radial overhand grip, they did not show a clear preference for this grip. Related to our study, this grasping behavior suggests that it should not have been a barrier for the infants to grasp the contralateral handle with an ulnar overhand grip with their preferred hand. Nevertheless, restricting infants' grasping to their preferred hand in our study may have biased infants' grasping behavior. Possibly, infants would have reached for the contralateral side more often when given a free choice of the grasping hand, using a radial overhand grip with the non-preferred hand. On the other hand, the observed bias to grasp the ipsilateral handle could also be due to an existing side preference in grasping. This assumption is supported by a study by Hauf et al. (2012), in which 9- and 11-month-olds showed a side-bias to the ipsilateral side when grasping heavy and light cubes. Hauf et al. compared infants of the same age group in different experiments, where the children either knew about the object weights and preferably grasped the lighter objects, or did not know about them and showed a side-bias. The authors assumed that children fell into a pattern of repetitive ipsilateral grasping if they could not distinguish between the objects. If they knew which of the two presented objects was heavier, a side-bias was less likely. In our study, infants were in principle able to discriminate between the materials, as indicated by their results in the visual-haptic condition regarding contralateral grasps. We assume that, in the ipsilateral grasps, this developing ability was overruled by a strong intrinsic motor tendency to grasp to the side of the grasping hand. This assumption is supported by a study by Corbetta and Snapp-Childs (2009), which showed that such intrinsic motor tendencies characterize infants' grasping, which might interfere with the emergence and consistent maintenance of new motor behavior. Altogether, the observed same-side bias in our study could be due to a predominant intrinsic motor tendency to grasp to the side of the grasping hand, combined with a preference for a radial overhand grip (Keen et al., 2014; McCarty et al., 1999, 2001), which together overrides potentially existing tendencies to consider object rigidity.

Second, with regard to our question whether handle material affects infants' grasping behavior, we found that the 11-month-old infants did not use object rigidity information for efficient grasping. Although most 11-month-old infants grasped the soft handles most frequently in all conditions and both grasping sides, the only significant preference for the soft handles was found in the visual-haptic condition in contralateral grasps. Thus, our results suggest that rigidity plays a surprisingly minor role in grasping behavior of infants, at least when material information is only presented visually. It could be that a more distinct preference for the soft handles was masked by the existing side-bias. Since the children were strongly driven to grasp the ipsilateral handle, the apparent softness preference is most evident in the few trials when grasping the contralateral handle. Adults, by contrast, showed no side-bias and preferred to grasp the rigid handles in both conditions. This indicates that adults' object usage was strongly affected by material rigidity and that they adapted their grasping actions to the object materials.

Third, we investigated the importance of dynamic visual and haptic object information on infants' grasping behavior. On the one hand, 11-month-old infants were not able to infer from the visual material information that the rigid handle would allow them to lift the object more easily. This raises the interesting question of whether this reflected a perceptual effect (i.e., inability to interpret the visually perceived deformation as an indicator of nonrigidity), a failure of physical reasoning (i.e., a lack of explicit cognitive understanding how rigidity affects the behavior of objects), or a lack of sensorimotor association linking rigid materials with better grasping outcomes than nonrigid ones (or indeed some combination of these). We cannot be sure whether infants differentiated between the materials at all despite clear deformation cues to indicate the non-rigidity. This contradicts the results of Imura et al. (2015), which indicated that 11-month-olds infer differences in object rigidity from visual motion information only. However, our study required participants not only to infer the different rigidity of handles, but also to use that information when grasping and lifting an object. Thus, we can conclude that, although 11-month-olds seem to be able to discriminate rigid and soft objects based on visual information alone, as shown by Imura et al. (2015), they still have difficulty using this information for efficient grasping. Furthermore, Paulus and Hauf (2011) showed that the knowledge about another material property, namely object weight, is well established at the end of the first year of life, indicating that the perception of different object properties might not develop simultaneously in infancy. Visual information was sufficient for 11-months-olds to preferentially grasp the lighter objects, and additional haptic exploration enabled even younger children to make predictions about an object's weight. Future studies might use Paulus and Hauf's (2011) design to test infants' grasping behavior in a preferential grasping task with two cubes of different material rigidity to find out more about infants' ability to visually discriminate between soft and rigid materials.

On the other hand, as expected, we did find that infants' manual object exploration facilitated the distinction between different object rigidities. In the visual-haptic condition, regarding the contralateral grasps in particular, infants reached for the soft handles more often. This implies that they did not use the material information for functional grasping: as soft handles deformed under the heavy object weight, grasping them made lifting the object more difficult. Rather, the haptic material information seems to motivate infants to repeatedly touch the soft material. De Campos et al. (2011) also reported higher grasping frequencies towards soft wool pompons compared to rigid polystyrene balls. Our study extends this finding by controlling for differences in surface appearance and shape. As a result, we conclude that 11-month-olds tend to prefer soft materials, which is especially evident when rigidity is perceived both visually and haptically. Possibly, material softness is associated with pleasant haptic memories such as the mother's skin or cuddly toys (cf. Pasqualotto et al., 2020).

Fourth, we aimed to investigate kinematic differences in reaching depending on rigidity and the different sensory conditions. Contrary to our expectations, the only kinematic parameter influenced by rigidity was trajectory straightness. In adults, the effect was as expected: their reaching movements were straighter towards the rigid materials, which is in line with studies that showed less repositioning and more detailed grasp planning for rigid materials (Barrett et al., 2008). Also, this reflects their preference for rigid handles which we have found in the frequency analyses. In the infants, however, the opposite was the case. Their trajectories were straighter for the soft materials. It remains unclear whether this difference was due to more practice (as they made more such reaches) or whether it was driven by the material per se; however, it indicates that the infants did not understand the easier lifting of the object by the rigid handle. No other kinematic parameter was affected by material rigidity, which is comparable to the results of Rocha et al. (2006), who showed no influence of rigidity on reaching trajectories in 4- to 6-month-old infants. If significant differences in reaching kinematics between soft and rigid handles had occurred, it would have been likely that task difficulty would also differ between the materials. However, since this was not the case, we can conclude that the soft material preference in infancy was not due to the lower demands of soft materials during grasping. Comparing the kinematics between conditions, we found that visual and visual-haptic information affected the grasping kinematics decisively. As expected, infants showed better fits of trajectories regarding straightness, MUs and relative reaching durations with additional haptic information compared to trajectories with only visual information. This could be related to the increasing ability of action planning with more object information and more specific object experience in early childhood. Also, it suggests that the planning of an appropriate reaching movement is easier with additional haptic information and emphasizes the importance of haptic information in infant grasp planning and execution. Furthermore, when comparing the kinematics between age groups, we found significant differences in all parameters. Infants' trajectories were slower than adults' (Ransburg et al., 2017) and the number of MUs decreased with increasing age (Rocha et al., 2006), approaching a minimum of 1 MU in adults (Morasso, 1983). Hence, our results confirm our expectation that the kinematics of grasping movements is not yet fully developed at 11 months. In adults, we found stereotypical kinematic motor patterns as described by Morasso (1983) and Konczak et al. (1995). In 11-month-old infants, we found higher intra-individual differences in reaching trajectories. The movements were less straight and showed many changes in direction and velocity, as expected. This could be a result of the improving ability in responding to the object demands during development. Also, this is in line with previous studies (Jansen-Osmann et al., 2002) that described early reaching movements as characterized by irregularities and multiple velocity peaks. Adult-like kinematics only occurs at the end of the second year of life in 75% of the reaching movements.

The present findings cannot answer the question when children start to consider information about rigidity for utilizing objects and implementing efficient grasping. To investigate the development of grasping behavior in infancy from an initial softness preference to a behavior considering material utility, we decided to examine older children with the same grasping task in Study 2. As described before, 16-month-olds were able to use information about object rigidity to optimize their motor behavior in a bridge-crossing task (Berger et al., 2005). Since this study did not differentiate between visual and haptic information and the entire body had to be moved for the motor task, the methodology differs considerably from our study. Thus, we decided to test even older children (3-year-olds) and expected a different behavior compared to the 11-month-olds in our task.

Study 2

To investigate whether infants' grasping preferences towards soft material would change with increasing age, we tested the performance of 3-year-old children in the same task. This age group was chosen because the children to be tested ought to be significantly older than 11-month-olds, since Study 1 showed that children at this age do not yet show any signs of grasping objects by the rigid handle. In addition, there are virtually no studies on the role of material properties on children's grasping behavior beyond the age of 2 years. At the same time, previous studies suggest that children at the age of 3 years have knowledge about various object affordances and other object properties. Moreover, predictive, goal-oriented reaching at that age is a familiar action with well-developed motor patterns (Jovanovic & Schwarzer, 2011, 2017; Konczak et al., 1995; Konczak & Dichgans, 1997; Rochat, 1995; Silva et al., 2011; Sveistrup et al., 2008). We therefore predicted that 3-year-old children would grasp rigid handles more frequently in both conditions, as compared to 11-months-olds. Furthermore, we expected straighter and faster trajectories with velocity profiles approaching the typical kinematic parameters of adults and less intra-individual differences.

1. Method

1.1. Participants

Twenty-five 3-year-old children took part in the study. They were recruited by obtaining their birth records from local municipal councils and neighboring communities and contacting their parents by mail. The group of 3-year-olds consisted of 13 female and 12 male children (M = 42.47 months; SD = 0.45; range: 41.55–43.20 months). One further child participated but did not complete the experiment due to shyness.

1.2. Stimuli and apparatus

They were the same as in Study 1.

1.3. Procedure

Testing of the 3-year-olds differed from Study 1 only with respect to the verbal instructions. To draw the children's attention to the experiment, the experimenter told the child that the object on the pillow was a snail that would like to go on holiday and therefore would need to leave its shell (the pillow). Every time the snail would return home, it would go back into its shell. The experimenter presented this scenario by placing a picture on the table between the child and the object, showing a different holiday destination for each trial. The experimenter explained that the child could help the snail to go on holidays by placing the snail on the picture. After that instruction, material properties of the handles were demonstrated as described in Study 1 and children were told to grasp the snail by one handle and to place it on the target picture. This instruction was used throughout the experiment, while conditions and the experimental procedure were the same as in Study 1. To eliminate side effects due to the position of the pictures, the target positions of the pictures were exactly on a straight line between the child's grasping hand and the middle of the test object. After testing, children received a small toy and a certificate.

1.4. Measures

All measures were the same as in Study 1. Each 3-year-old child completed all trials except for two children. One child completed only one visual trial and one child completed only four visual-haptic trials. All children except one used their right hand for grasping.

2. Results

2.1. Grasping frequencies and grasping sides

In contrast to adults and infants in Study 1, who used an overhand grip in all trials, few underhand grips were observed in 3-year-olds (23 out of 166 trials). They used an overhand radial grip on the ipsilateral handle about as often as they used an overhand ulnar grip on the contralateral handle (see Table 1).

First, we tested if grasping frequencies were affected by handle side. More than one third of the 3-year-olds showed equal grasping frequencies to both handle sides (37.5%; 9 of $n = 24$). About the same number of children grasped the ipsilateral handle more often (41.7%; 10 of n = 24), whereas one fifth of the children grasped the contralateral handle more often (20.8%; 5 of n = 24). Thus, the 3-year-olds showed a tendency towards a same-side bias, but a Chi-square test showed no significant difference between this grasping frequency distribution and chance ($p = .62$). Comparable to the analyses of infant data in Study 1, we conducted separate Chi-square tests for the ipsilateral and contralateral grasps in 3-year-olds, also taking the conditions (visual and visual-haptic) and materials into account. There was no significant relation between material and condition, neither when grasping the ipsilateral handles, nor when grasping the contralateral handles (all $p >$ .50). A closer look at the frequency distribution, however, showed that in both conditions, regardless of the grasping side, most children preferably grasped the rigid handle (see Fig. 8).

In order to compare the children's groups between Study 1 and 2, and since the 11-month-old infants from Study 1 showed a soft handle preference in the visual-haptic condition for contralateral grasps, we drew a comparison between these age groups in the corresponding condition. For trials in which children grasped the contralateral handles, a Chi-square test showed a significant relation between material and age group in the visual-haptic condition, $\chi^2(2) = 7.97$, $p < .05$, $\varphi = 0.50$. In this condition, the majority of the 11-month-old infants (88.9%) preferred the soft handles, whereas about one third of the 3-year-olds each preferred the rigid handles, (39.1%; $n = 9$), preferred the soft handles (34.8%; $n = 8$), or showed no preference (26.1%; $n = 6$; Fig. 9). This showed that the 11-month-olds' preference for the soft handles in contralateral grasps in the visual-haptic condition is no longer present in 3-year-olds.

Table 1
Number of trials in 3-year-olds using an overhand radial/ulnar or underhand radial/ulnar grip.

	overhand radial (ipsilateral)	overhand ulnar (contralateral)	underhand radial (contralateral)	underhand ulnar (ipsilateral)
Number of Trials	86	80	2	21

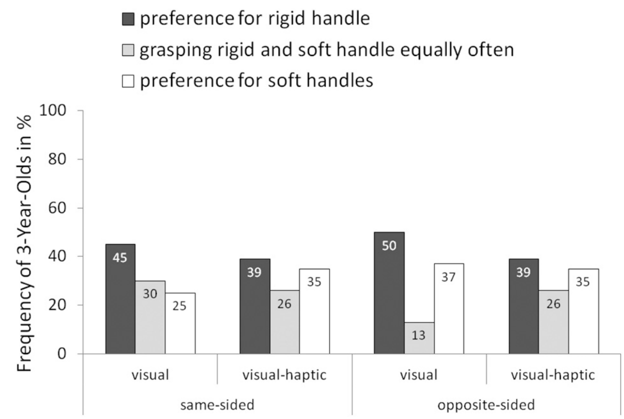

Fig. 8. Percentages of 3-year-olds' grasping behavior are shown in the visual and visual-haptic condition; separately for trials where they grasped the ipsilateral and contralateral handles (n = 24).

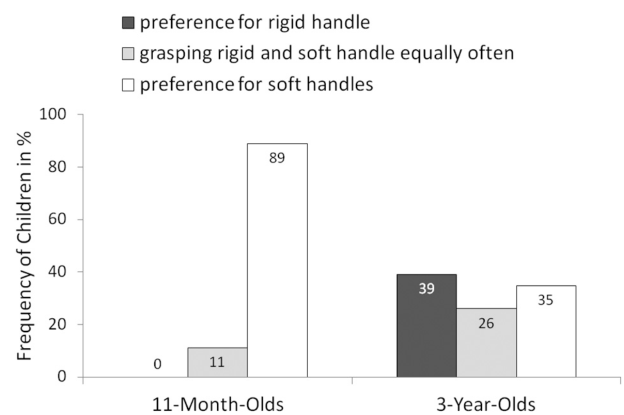

Fig. 9. Percentages of 3-year-olds' and 11-month-olds' grasping behavior are shown in the visual-haptic condition for contralateral grasps.

In conclusion, 3-year-old children still showed a tendency to grasp ipsilateral handles more often compared to contralateral handles. However, they no longer preferred soft materials as the 11-month-olds did in the contralateral grasps in the visual-haptic condition, but showed a tendency to prefer the rigid handles in all conditions. Nevertheless, their grasping behavior still differed from that of adults in Study 1, who clearly preferred rigid handles to lift the objects efficiently in both conditions.

2.2. Kinematic analysis

To find out about developmental differences in the first years of life, each kinematic parameter was compared between 11-month-old infants from Study 1 and 3-year-old children from Study 2 by calculating a mixed measures ANOVA with between-subject factor age group and within-subject factors material and condition. *t*-tests for independent samples showed no significant differences for any kinematic parameter between the ipsilateral and the contralateral handles in 3-year-olds (all p values $>$ .05). Thus, we averaged the kinematic variables across the grasping sides in all following analyses.

For mean reaching velocity, a significant main effect of condition was found, $F(1,232) = 4.51$, $p < .05$, $\eta_p^2 = 0.02$; with lower mean velocity in visual ($M = 0.29$ cm/s, $SD = 0.11$ cm/s) compared to visual-haptic condition ($M = 0.33$ cm/s, $SD = 0.11$ cm/s).

For relative reaching duration, a significant main effect of material was revealed, $F(1, 205) = 4.46$, $p < .05$, $\eta_p^2 = 0.02$, pointing to shorter relative reaching durations for soft ($M = 38.47$ ms/cm, $SD = 12.88$ ms/cm) compared to rigid materials ($M = 43.73$ ms/cm, $SD = 14.17$ ms/

cm). Another significant main effect of condition was found, $F(1, 205) = 8.67$, $p < .01$, $\eta_p^2 = 0.04$, showing higher relative reaching durations in the visual ($M = 45.91$ ms/cm, $SD = 14.21$ ms/cm) compared to the visual-haptic condition ($M = 39.42$ ms/cm, $SD = 13.24$ ms/cm). The main effect of age group was also significant, $F(1, 205) = 18.05$, $p < .01$, $\eta_p^2 = 0.08$, indicating surprisingly higher relative reaching durations in 3-year-olds ($M = 45.67$ ms/cm, $SD = 14.03$ ms/cm) compared to 11-month-olds ($M = 35.41$ ms/cm, $SD = 10.79$ ms/cm).

For movement units, a significant main effect of condition was found, $F(1,221) = 17.33$, $p < .01$, $\eta_p^2 = 0.06$, with a higher number of MUs in the visual ($M = 2.22$, $SD = 0.98$) compared to the visual-haptic condition ($M = 1.81$, $SD = 0.77$). The ANOVA also revealed a significant main effect of age group, $F(1, 221) = 21.11$, $p < .01$, $\eta_p^2 = 0.08$, with fewer MUs in 3-year-olds ($M = 1.81$, $SD = 0.79$) than in 11-month-olds ($M = 2.05$, $SD = 0.77$). A significant interaction for age group and condition was found, $F(1, 221) = 18.04$, $p < .01$, $\eta_p^2 = 0.06$, indicating a decrease in the number of MUs in 11-months-olds from visual ($M = 2.91$, $SD = 0.89$) to visual-haptic condition ($M = 1.81$, $SD = 0.73$) and a slight increase in 3-year-olds from visual ($M = 1.79$, $SD = 0.78$) to visual-haptic condition ($M = 1.81$, $SD = 0.81$).

Among all reaching parameters, no other main effect and no interaction between age group, material and condition were significant ($p > .05$). In summary, 11-month-olds and 3-year-olds reaching trajectories differed significantly in the amount of MUs. 3-year-olds' trajectories contained less decelerations and accelerations than 11-month-olds' reaching movements, indicating higher reaching precision in older children (Fig. 10). 3-year-olds' trajectories resembled those of adults, showing less intra-individual differences compared to infants' trajectories. However, 3-year-olds' number of MUs did not differ between visual and haptic condition, whereas 11-month-olds benefited from additional haptic information, leading to fewer MUs in the visual-haptic condition compared to the visual condition.

3. Discussion

In Study 2, the grasping behavior of 3-year-old children was tested using the same setup as in Study 1. First, 3-year-olds showed no significant grasping side-bias. However, they still tended to grasp the ipsilateral handles more often compared to the contralateral handles, but this effect was no longer as strong as in the infant group. This is consistent with previous studies (Stilwell, 1987), which have shown

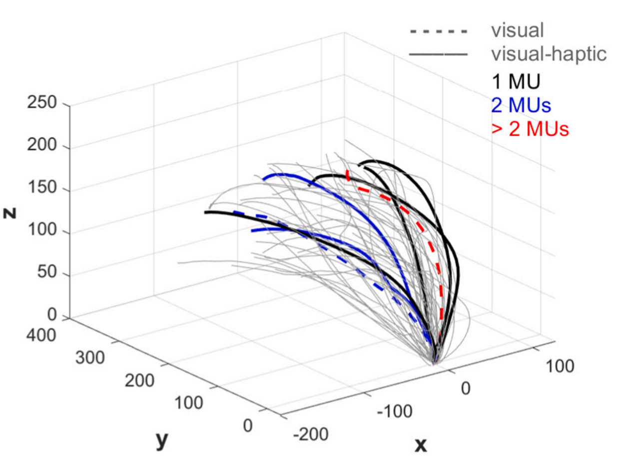

Fig. 10. An example selection of reaching trajectories of 3-year-old children. Highlighted are all trajectories from one child. The colors indicate the number of MUs: black 1 MU, blue 2 MUs, red >2 MUs. Line type represents the condition: - - visual condition, −visual-haptic condition. Trajectories have been shifted to the same starting point for better comparison. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

preferred grasping to ipsilateral objects in preschoolers and an increase of contralateral grasping frequency with age. As 3-year-olds used an overhand radial grip on the ipsilateral handle about as often as they used an overhand ulnar grip on the contralateral handle, one could conclude that their slight side-bias was not due to a preference in grip orientation, but rather a preference to grasp the ipsilateral handles.

Furthermore, 3-year-olds did not significantly prefer any of the materials in any condition, indicating that their grasping behavior was predominantly guided by other factors than rigidity. This is not in line with our prediction that children at that age should take information about rigidity into account when utilizing objects. Even after haptic exploration, they did not grasp the rigid handles significantly more often; however, they tended to prefer the rigid handles.

On the one hand, one might ask whether children in our study were unable to judge the efficiency of grasping the handles or to extract the underlying information relevant for this judgment, because they failed to combine the visual and haptic information presented to them. Some previous studies suggest that vision and haptics are still not well integrated even at preschool age (e.g. Kalagher & Jones, 2010). However, the evidence regarding such integration is somewhat controversial, as other studies indicate that redundant sensory information, presented in temporal synchrony to at least two different senses, leads to enhanced differentiation of object perception (e.g. Bahrick, 2004; Bahrick & Lickliter, 2002; Jovanovic et al., 2008; Wilcox et al., 2007). In addition, there is also some supporting evidence in favor of children's ability to integrate visual and haptic information for judging efficient action. As an example, even 16-month-old children have been found to use material information of a handrail to decide whether they could cross a bridge (Berger et al., 2005). The main difference between their task and our experiments is that between whole body motion and grasping. In Berger et al. (2005), children might have leaned against the handrail with their whole body instead of just exploring the material with their hands. Also, their task was associated with a higher risk and potentially more motor experience. Thus, it seems that understanding and making use of object materials is task-specific, and might be better in situations involving the whole body rather than grasping.

On the other hand, the absence of a material preference does not necessarily mean that the 3-year-old children did not perceive any difference between the handles. Rather, when comparing all three age groups from Study 1 and 2, we can see clear age-related changes in the distribution of grasping frequencies. 3-year-olds showed a higher preference for the rigid handles compared to 11-month-olds which indicates that they anticipated the functionality of the materials to some extent. But still, their grasping frequency to the rigid handles was much lower compared to the adults. This suggests that 3-year-olds are on an intermediate level in the development from (1) preferring the pleasant sensation of a soft fabric (11-month-olds), to (2) preferring the efficient rigid handle (adult).

Future studies might conduct our experiment with even older children, to determine at which age children start to preferably reach for the rigid handle. Indeed, it would be particularly interesting to perform a longitudinal study to trace the transition within individual infants and relate it to the development of other sensorimotor and cognitive capabilities. This would likely support the findings of Krnel et al. (2003) who showed that children pay attention to materials only relatively late in development. With the aim of studying the development of object concepts, they asked 3- to 13-year-old children to classify objects of different materials (metal, wood, plastic, organic material) varying in shape, size, action and color. As a result, children at the age of 3 years had difficulties in grouping the objects and only very few of them classified the objects by shape and color. Only at the age of 5 years did children start to classify objects according to their material, and these classifications further increased in children from the age of 11 years on.

Our study is one of the few studies that examined and analyzed the reaching kinematics in 3-year-old children and 11-month-olds infants in detail. Our results showed that reaching trajectories were only slightly affected by object rigidity, but much more substantially by visual versus visual-haptic condition and age. Similar to 11-month-olds and adults in Study 1, rigidity affected only a single kinematic parameter in 3-year-olds. Their relative reaching durations were shorter when children grasped the soft compared to rigid handles. This was unexpected, as 3-year-olds did not show a preference for soft handles and suggests that grasping soft materials is less demanding for older children (De Campos et al., 2011) or has been practiced more frequently (discussed in Study 1). It could also be an indication that they were still more comfortable grasping the soft handles like the 11-month-olds, although, at the same time, they seem to have overcome their preference for soft materials in terms of grasping frequency. Besides material rigidity, our results showed that the visual and visual-haptic conditions affected the kinematic parameters. As in infants and adults, reaching durations were shorter in the visual-haptic condition in 3-year-olds, suggesting that the planning of an appropriate reaching movement is easier with additional haptic information.

When comparing the kinematic parameters between age groups, results were generally in line with our expectations. While infants' reaching trajectories showed a lot of variability, 3-year-olds' trajectories much more resembled those of adults (Konczak & Dichgans, 1997). Interestingly, relative reaching durations were higher in the older children. Potentially, the instruction to place the object on the picture in front of the child influenced reaching speed by an additional attentional demand on more precision. Claxton et al. (2003) showed a similar effect: adults, as well as 10-month-old infants reached faster for a ball in a throwing task compared to a task where they had to fit the ball in a tube, which required more precision. However, because of the lower age it was not possible in the present study to instruct the 11-month-olds to place the object on a specific location on the table.

One limitation of both Study 1 and Study 2 is the higher number of trials in the visual-haptic condition compared to the visual condition, and the confounding in the order of conditions. This resulted in more reaching and grasping practice in the visual-haptic condition. Especially with respect to the kinematic parameters, it cannot be ruled out that the improvements from the visual to the visual-haptic condition are partly explained by more practice. Future studies should examine two groups, each tested in only one of the conditions, to avoid learning effects and confounding of presentation order. Moreover, it has to be considered that the total number of trials may not have been sufficient for young children to make use of prior object encounters in later reaching movements. This has also been discussed by Corbetta and Snapp-Childs (2009), who found no changes in reaching behavior in 6- to 9-month-olds even after 10 trials with the same object. While adults immediately start off with functional reaching movements, young children might need more practice to develop efficient reaching strategies and to adjust their reaching behavior to the perceived material properties. Therefore, future grasping studies with young children should consider using more trials and a greater variety of objects. In addition, as we designed the objects to be so heavy that infants only could just lift them, it was likely easier for adults to the lift the objects. However, note that this should have motivated the infants even more to choose the more functional handle, which was not the case. Furthermore, the infants did not have a specific goal while lifting the object, as did the 3-year-olds and adults. Nevertheless, they lifted the objects as expected. However, it should be noted that this may have led to motivational differences for the reaching action between the groups.

Conclusion

In conclusion, this research suggests that taking rigidity into account when reaching and grasping objects efficiently is subject to a long developmental process. When lifting relatively heavy objects with soft and rigid handles, young children did *not* use information about handle rigidity for efficient reaching and grasping movements; although they are able to distinguish handle materials. 11-month-olds showed a tendency to prefer soft materials in all conditions, but only significantly preferred soft materials in the visual-haptic condition when grasping the contralateral handle. In adults, this changed into a modality-independent preference for rigid materials. Our findings suggest that the transitional point from a preference for soft to one for rigid materials, and for being able to use visual and haptic material information for efficient reaching movements, is later than the age of 3 years, at least under the present conditions.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Declaration of competing interest

None.

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