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RESEARCH ARTICLE

Effects of the Ebbinghaus illusion on children's perception and grasping

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Abstract We investigated the development of the Ebbinghaus illusion in children's perception and grasping. A previous study (Hanisch et al. 2001) had reported negative illusion effects on 5- to 12-year-olds' grasping as compared to their perception. We attempted to replicate this finding and to test different hypotheses based on a direct influence of the context elements on the trajectories of the fingers which could explain this reversal of the illusion effects. For 5- to 7- and 9- to 11-year-olds we observed the classical illusion effects in perception. Illusion effects were perfectly similar for perception and grasping in 9- to 11-year-olds, while there was a non-significant trend toward smaller illusion effects in grasping for the 5- to 7-year-olds. This could be due to a slightly different effect of the illusion on younger children's grasping. However, it seems clear that there are no qualitative changes, as a reversal of the illusion effects in grasping of younger children. Finally, we show that our grasping data conform well to the motor literature for children's grasping, thereby strengthening our conclusions.

Keywords Ebbinghaus illusion · Children · Grasping · Visual pathways

Introduction

During the last years the question of how visual illusions affect perception and action has drawn large interest. The underlying assumption is that different illusion effects in perception and action would reflect the functional separation of the dorsal and ventral pathway of the visual system as stated by Milner and Goodale (1995). In their account the processing of visual information used for the visual recognition of objects is attributed to the ventral pathway whereas the processing of visual information for guiding motor actions is attributed to the dorsal pathway. Geometrical visual illusions clearly deceive our conscious perception and are related to object recognition processes (Coren and Enns 1993) and therefore might be supported by the ventral pathway. Processing the same visual illusion stimuli for motor actions might be supported by the dorsal pathway and according to Milner and Goodale might lead to different effects. A series of studies tested this assumption by studying the effects of the Ebbinghaus illusion for perception and action. Whereas most of these studies examined these effects in adults the present study aimed to analyze the development of this relationship in children.

The Ebbinghaus illusion consists of an inner circle that is surrounded by an annulus of either larger or smaller circles (Fig. 1). We perceive the central circle smaller when it is surrounded by larger circles than when it is surrounded by smaller circles. The effect of this illusion on action was usually measured by inspecting the maximum grip aperture (MGA) of grasps for the central circle of an Ebbinghaus illusion figure. Thereby the central circle is commonly presented as a three-dimensional disc. During grasping thumb and index finger open to a MGA which is linearly related to the object size (Jeannerod 1981, 1984). The MGA is formed before the fingers touch the object and thus it indicates the size information in the motor system. To what extent this information relies on the physical size or the illusionary size of the central circle of an Ebbinghaus figure can demonstrate whether motor performance is also deceived by the illusion.

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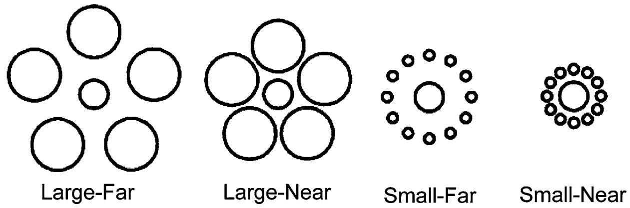

Fig. 1 The four different versions of the Ebbinghaus illusion used as stimulus. The conditions varied in the size of the *context circles* (Large, Small) and the distance between *context circles* and *central circle* (Near, Far). The stimuli are identical to the stimuli used by Franz et al. (2003) with adults

Previous studies comparing the illusion effect on visual awareness to the illusion effect on motor performance came to contradictory conclusions: on the one hand, it has been reported that grasping is deceived by the Ebbinghaus illusion far less than our visual awareness (Aglioti et al. 1995; Haffenden and Goodale 1998; Haffenden et al. 2001), while on the other hand a series of experiments has demonstrated that the motor system is deceived by the illusion in the same direction and to about the same extent as our visual awareness (Franz et al. 2003, 2000; Pavani et al. 1999).

While the different outcomes are controversially debated (Bruno 2001; Carey 2001; Franz 2001; Franz and Gegenfurtner 2007) the analysis of the developmental course of these illusion effects can help to understand further aspects of the dynamics and potential interactions between the two pathways of the visual system. In principle, four different relationships between the developmental courses of the perceptual and grasping illusion effects can be differentiated: (1) the effects are equal throughout development, indicating that they are based on common mechanisms. (2) The illusion effects differ clearly from each other throughout development, showing that the illusion affects the dorsal and ventral pathways differently. (3) The illusion effects are dissociated at early ages and merge to effects of about the same size with increasing age, indicating that originally the illusion effect is generated in one of the two pathways. With increasing age, specific processes, such as the development of an increasing cross-talk between the two pathways, transfer the illusion effect to processes of the other pathway. (4) There are uniform illusion effects for perception and grasping in early childhood which diverge with age ending up in a strong dissociation between perceptual and motor effects in adults. This could be caused by the functional maturation of the dorsal and ventral pathway. In this case adults' illusion effects for perception and grasping should be attributed to distinct processes generated independently of each other.

The development of the relationship between motor and perceptual effects of the Ebbinghaus illusion has hardly ever been examined. Developmental aspects have mainly been examined for the perceptual illusion effects only. It has been found that 4-year-old children show the typical illusion effect in their perception and that the effect increases with age (Káldy and Kovács 2003; Weintraub 1979; Zanuttini 1996). Weintraub describes an increase between 6 and 8 years, Zanuttini observed it between 4 and 6 years, and Kaldy and Kovács found it between 4 years of age and adulthood. There is only one study carried out by Hanisch et al. (2001) that investigated the effects of the Ebbinghaus illusion on children's grasping as compared to their perception. This study will be described later in more detail.

Before studying the developmental course of illusion effects on grasping it has to be taken into account that not only the illusion effects but also grasping per se develops. Kuhtz-Buschbeck et al. (1998) examined the development of prehension movements of 4- to 12-year-old children who grasped for cylindrical objects. They observed that 4- to 5-year-olds adjust their maximum preshape aperture to the perceived size of an object. Moreover, they found children's MGA to be timed within the second third of the reach as it is reported in many studies for adults (Smeets and Brenner 1999). Also, kinematic grasping parameters, such as a symmetric pattern in acceleration and deceleration phase are developed at this age (Paré and Dugas 1999). Thus, it is appropriate to investigate the illusion effects of 5-year-olds' and older children's grasping in the same way as in adults.

As mentioned above, Hanisch et al. (2001) studied the development of the Ebbinghaus illusion in perception and grasping. Besides analyzing the perceptual judgments of 5- to 12-year-olds, they analyzed their MGA when they grasped for the central disc of an Ebbinghaus figure. The illusion effect on perception was equal for children and adults and similar to the illusion effect observed for adults in similar studies (Aglioti et al. 1995). However, they observed a negative illusion effect on grasping in the children's group which was more pronounced in 5- to 7-year-olds than in 8- to 12-year-olds. Thus, the children used a larger MGA for discs which they judged to be smaller and vice versa. Adults' grasping, in contrast, was deceived by the illusion in the same direction as their visual judgments.

Hanisch et al. (2001) explain the negative illusion effect on grasping in children by effects of a kind of obstacle avoidance mechanism. They suggest that the children adjusted their MGA not to the perceived size of the target disc but rather to the absolute distance between target disc and surrounding annulus. This gap was larger for the large context circles than for the small context circles (see the Large-Far and Small-Near conditions in Fig. 1). In order to avoid contact with the surrounding annulus, children might have used a smaller grip aperture for the small illusion contexts.

A similar obstacle avoidance mechanism was used as an explanation for the illusion effect in some studies with adults by Haffenden and Goodale (2000) before. Haffenden and Goodale, however, proposed that only the large context circles might be treated as potential obstacles by adults. The small context circles were too close to the target disc and adults might not have tried to adjust their grip aperture to this too narrow gap. Hanisch et al. (2001) assumed children's finger size was sufficiently small to grasp into the large and small gaps. This explains why Hanisch et al. use the obstacle avoidance mechanism as explanation for a negative illusion effect and Haffenden and Goodale for the normal illusion effect. The interpretations of Hanisch et al. and Haffenden and Goodale are identical to the point that the surrounding context elements had an influence on grasping, but they differ in their final conclusion. Hanisch et al. interpret the influence of the context elements on grasping as evidence for the motor performance relying on allocentric visual cues and therefore for an interplay between the dorsal and ventral pathways. In contrast, Haffenden and Goodale interpret their results in terms of differences between the illusion effects on perception and motor performance and in favor of a dissociation of the dorsal and ventral pathways.

Franz et al. (2003) tested the effect of an obstacle avoidance mechanism in detail and showed that it cannot explain the illusion effects in adults. They tested the illusion effects on adults' perception and grasping by presenting Ebbinghaus illusion contexts where the gap sizes in the Small and Large conditions were systematically controlled (Near and Far gaps for both conditions, see Fig. 1). Both, in grasping and perception the results yielded the typical illusion effect in the Small-Far and the Large-Far context and in the Small-Near and Large-Near contexts. Thus, an adjustment of the MGA to the gap size cannot explain adults' grasping effect.

This result also casts doubt on Hanisch et al.'s (2001) obstacle avoidance mechanism as an explanation of the negative illusion effect on grasping in children and motivates to study this explanation in more detail in children, too. However, besides the obstacle avoidance mechanism there is also another explanation for the negative illusion effect on grasping. Instead of presuming that children tried to reach into the gap between target and context circles, we can assume that children adjusted their grip aperture to the overall size of the Ebbinghaus context, namely to the diameter of the annulus. As the diameter of the annulus was smaller for the Small context condition compared to the Large context condition this would also lead to the negative grasping effect.

By adopting the stimuli from Franz et al. (2003) (see Fig. 1) we investigated whether children's grasping of the central disc in an Ebbinghaus figure is determined by a grip adjustment to the gap size between circle and annulus or by a grip adjustment to the overall stimulus size.

If children's grasping corresponds to the gap size, we expect them to grasp with a larger MGA for illusion contexts with a large distance between central disc and annulus independent of whether the context is Small or Large and vice versa. If children adjust their MGA to the overall size of the illusion context, the MGA should increase with an increasing diameter of the illusion context. Finally, if grasping is deceived in the same direction as perception, we would expect a larger MGA for those discs which are surrounded by small context circles than for those surrounded by large context circles.

Taken together, in the present study we further investigated the Ebbinghaus illusion in children's perception and grasping. Motivated by Hanisch et al.'s (2001) findings of a negative illusion effect on grasping the study was designed to analyze whether children's grasping is oriented to the gap size between the inner circle and annulus or to the overall size of an Ebbinghaus figure.

Methods

Participants

Twenty-one 5- to 7-year-old (mean age 6 years 11 months; range 5 years 8 months to 7 years 9 months; 13 female, 8 male) and twenty-one 9- to 11-year-old (mean age 10 years 4 months; range 9 years 0 months to 11 years 1 months; 11 female, 10 male) children participated in this study. One of the 5- to 7-year-olds and one of the 9- to 11-year-olds performed a perceptual task only, whereas the others performed a perceptual and a grasping task. All participants were right-handed and had normal or corrected to normal vision. Parents gave informed consent to the participation of their children prior to testing. As a reward for their participation children received a small present at the end of the experimental session.

Because our results differed from the results of Hanisch et al. (2001) we performed a power analysis (Cohen 1988). Hanisch et al. reported a mean illusion effect of $\delta = -2.3$ mm ($SE = 0.7$ mm) for 5- to 7-year-olds which was based on measurements of $N = 8$ individuals. Thus the standard deviation of the 5- to 7-year-olds effect was $\sigma = 1.98$ mm, and consequently the effect size was $d = \delta/\sigma = -2.3/1.98 = -1.16$. If we assume that this effect is true and that we want to detect a negative effect of this size with our larger sample size ($N = 19$—our analysis of the 5- to 7-year-olds' grasping was based on data of 19 of the 21 tested participants) this results in a statistical power of 99.9% (one-tailed-test, $\alpha = 5\%$). In other words the probability of missing this effect if it exists was as small as $\beta = 100-99.9\% = 0.1\%$ for the 5- to 7-year-olds. Analogously for the 8- to 12-year-olds of Hanisch et al.'s study ($\delta = -1.3$ mm, *SE* = 0.8 mm, *N* = 12, $\sigma = 2.77$ mm) the effect size was $d = \delta/\sigma = -1.3/2.77 = -0.47$. With our larger sample size of *N* = 20 (our analysis of the 9- to 11-year-olds' grasping was based on data of 20 of the 21 tested participants) this leads to a statistical power of 64.9% (one-tailed-test, $\alpha = 5\%$) and consequently the probability of missing this effect if it really exists with our sample size was 35.1%. This shows that the probability to miss the effect of Hanisch et al. due to random statistical fluctuations was quite low—at least in the 5- to 7-year-olds.

Stimuli

Stimuli were exactly the same as used by Franz et al. (2003). We used four different conditions of the Ebbinghaus illusion, in which the size of the context circles (Small, Large) and the distance between context circles and target disc (Near, Far) were varied independently (Fig. 1). In the "Small" conditions the central target disc was surrounded by an annulus of twelve small circles, which were 10 mm in diameter. In the "Large" conditions the central target disc was surrounded by an annulus of five large circles, which were 58 mm in diameter. The distance between the midpoint of the target disc and the nearest point of the context circles was 24 mm for the "Near" and 31 mm for the "Far" conditions. All context circles were printed on white cardboard. Aluminum discs, 28, 30, and 32 mm in diameter (corresponding to 4.58°, 4.91°, and 5.23° of visual angle) and 5 mm in height, with a white surface and a black outline were used as target discs. All of the twelve combinations of the four illusion contexts and the three target sizes were used as stimuli.

In the perceptual task further comparison discs were used. They were equal to the target discs, except for their diameters lying within the range of 24–36 mm with 1 mm increments.

Apparatus

The experimental setup is depicted in Fig. 2. Participants sat on a stool and used a chin rest to keep a constant viewing distance throughout the experiment. They looked down at a table on which a white wooden presentation-board was placed. The board was 46 cm wide and 24 cm high. At the center of the board, and at a horizontal distance of 15.5 cm to the left and to the right of the center, small metal spikes were located, which served as mountings for the aluminum discs. The board was tilted 66° against the table surface, so that the participants' gaze direction was perpendicular to the presentation surface. The board was positioned well within reach of a child at a viewing distance of ~35 cm, with its horizontal center being aligned to the participants' center along the medio-lateral body axis. Six-cm in front of the presentation board with a horizontal offset of 8 cm to the right from the horizontal center, a small spot on the table indicated the start position. On top of the fingernails of thumb and index finger of the right hand an infrared light-emitting diode (LED) was attached with a small piece of plasticine (Fig. 2b). The position of the LEDs was recorded with a sampling rate of 100 Hz using an Optotrak system.

Procedure

Half of the participants first performed the perceptual task whereas the other half began with the grasping task.

Perceptual task

One of the illusion contexts was placed centered on the presentation-board (see Fig. 2a). In the middle of the illusion context one of the target discs was positioned on the central spike. An isolated comparison disc was

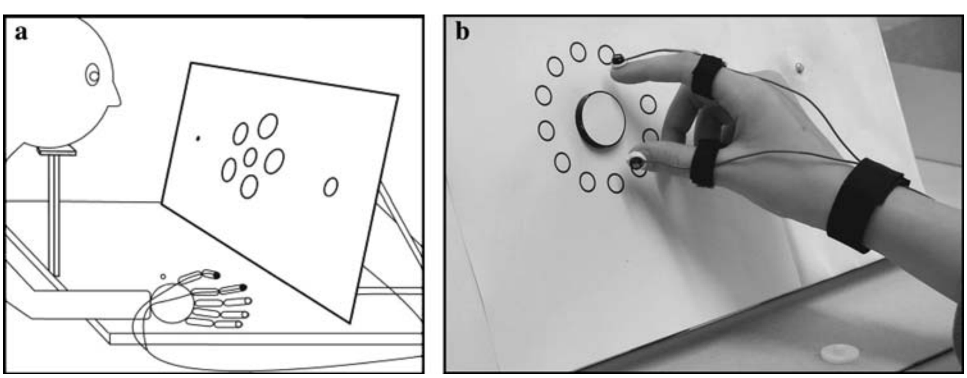

Fig. 2 Experimental setup: a single illusion figure was presented in the center of a tilted presentation platform. **a** In the perceptual task an isolated comparison disc was presented to the left or to the right of the illusion context and the participant was asked to judge whether the comparison disc is smaller or larger than the target disc in the center of the illusion context. **b** In the grasping task children had two Optotrak-markers attached to thumb and index finger and grasped the target disc

placed on one of the outer spikes, randomly to the left or to the right side of the illusion context. The participant was asked to judge which disc was larger. These forced choice comparisons were performed repeatedly using a staircase design. Each staircase began with a comparison of a target disc and a comparison disc that was either 3 mm larger or smaller. When the participant judged the comparison disc to be larger (smaller), it was replaced with a 1 mm smaller (larger) disc and the participant was asked to compare the new pair of discs. When the participant's answers changed for the third time from smaller to larger or from larger to smaller, the staircase was terminated and the session continued with a new staircase for another illusion context with another target size. Each child performed the staircases for a minimum of 6 and a maximum of 12 of the 12 possible context-target combinations. The actual number of performed staircases depended on each child's ability and willingness to cooperate. The task was terminated when a child showed indications of fatigue, boredom, or lack of concentration. The presented conditions were as balanced as possible for each child, meaning that any context type was presented at the most once more than any other context type. Within each age group the 12 combinations were judged equally often.

Grasping task

At the beginning of each trial an illusion context and a target disc were placed on the presentation board, as in the perceptual task. Participants placed their thumb and index finger in a pinch position at the start point. At the experimenter's signal they grasped the disc with their right hand, lifted it and moved it to the side. Then the experimenter fetched the target disc and prepared a new trial. Participants had full vision during grasping. The experimenter monitored the recorded grasp-trajectories on a computer screen right after each trial and returned unsuccessful grasps and those with missing markers to the set of trials to be performed. These trials were repeated at a randomly determined later time. Note, that only obviously invalid trials were excluded due to this online inspection. A more detailed offline inspection followed after the data collection. Each child performed six or seven blocks of 12 trials, depending on their ability to concentrate on the task. Within each block all 12 context-target combinations were presented once in a random order, such that each child repeated each condition six–seven times.

At the beginning of the grasping task three practice trials were performed. Children had to grasp a disc, that was positioned without illusion context on the presentation board, and differed from the target discs in its size.

Data analysis

Perceptual task

For each trial the perceived size of the target disc was obtained by calculating the mean of the three turning points of each staircase. The turning points were the mean sizes of the comparison discs of two consecutive trials in which the participant's answer changed from smaller to larger or from larger to smaller. By subtracting the physical size of the target disc from the perceived size we obtained our perceptual measure, the perceptual-size-difference. For each participant the perceptual size difference of each tested illusion condition was submitted to the later analysis.

Grasping task

The grip aperture was calculated as the absolute distance between the two LEDs attached to thumb and index finger. In a first step, the start of the reach and the end of the reach were detected automatically with a custom made analysis program written in the Matlab programing language (The MathWorks Inc., Natick, MA, USA). The start of reach was defined as the first time the velocity of index finger or thumb exceeded 0.1 m/s. The end of reach was determined as the first time the velocity of the thumb or index finger was below 0.5 m/s and one of the fingers was closer than 30 mm from the center of the target disc.

Due to the large variability in children's grasping we controlled the automatically detected start- and stop-points for each trajectory in an offline inspection. Those trajectories, in which the start of reach, the maximum of the reach or the end of reach could not be detected due to missing markers, were excluded from further analysis. For those trajectories, for which the automatic detection of start and end of reach obviously led to erroneous starting points (e.g., due to an early movement onset which was not related to the actual grasp) the start and stop points were adjusted manually to plausible start points.

Eleven percent of the originally 3,180 trials were excluded and in 16% of the remaining trials the automatically detected starting and stop points were adjusted manually. From one 7-year-old participant 56% of the trials had to be excluded, and therefore the complete grasping data from this participant were excluded from all analyses.

The MGA was defined as the maximum in grip aperture between start of reach and end of reach. For each participant the mean MGA was calculated for the 12 illusion conditions. This mean MGA was submitted to the later analysis. The total movement time was defined as the time between start of reach and end of reach. The relative timing of MGA refers to the percentage of movement duration at which the MGA was observed within each grasp.

For additional post hoc analyses we used the data of 4- to 12-year-old children's maximum finger span which was provided in a study of Kuhtz-Buschbeck et al. (1998). Kuhtz-Buschbeck et al. observed a maximum finger span of 9.8 cm for 48- to 51-month-olds, of 10.6 cm for 60- to 63-month-olds, of 11.7 cm for 84- to 87-month-olds, and of 14.3 cm for 144- to 147-month-olds. We performed a linear regression analysis of these data and, on the basis of this regression, estimated the maximum finger span for each of our participants. The normalized MGA was obtained as the MGA's percentage of these estimated maximum finger spans.

Comparison of the perceptual and motor effects

For a comparison of illusion effects in perception and grasping, we calculated corrected illusion effects. These were calculated by dividing the raw illusion effects, which were pooled across the distance of context (Near and Far), by the slopes of the functions that relate physical size to the dependent measure (Franz 2003; Franz et al. 2001, 2005; Glover and Dixon 2002) (see also the Result section for the rationale behind this correction). To estimate the variability of the corrected illusion effect, we used the delta method (i.e., a linear Taylor approximation) (cf. Franz et al. 2005; Franz 2007).

Results

Illusion effect on perception

The perceptual-size-difference served as the dependent variable in a repeated measure analyses of variance (ANOVA) with the factors context-size (Small, Large), context-distance (Near, Far), and age (5- to 7- and 9- to 11-year-olds) (Fig. 3a). A significant main effect of context-size, $F(1, 40) = 124.06$, $P < 0.001$, indicates the typical effect of the Ebbinghaus illusion: participants perceived the target disc as larger when it was surrounded by small context circles and perceived it as smaller when surrounded by large context circles. A significant interaction of age and context-size, $F(1, 40) = 6.83$, $P = 0.013$, reveals this effect to be stronger in younger children than in older children. Further, a main effect of context-distance, $F(1, 40) = 5.74$, $P = 0.021$, shows that participants perceived the target discs as larger in the Near conditions than in the Far conditions. Finally, a significant interaction of context-size and context-distance, $F(1, 40) = 13.71$, $P = 0.001$, revealed this effect was larger for the "Small" context circles, whereas there was no difference between "Near" and "Far" within the "Large" context circles. No further significant main or interaction effects were observed (all P's > 0.19). Note, that

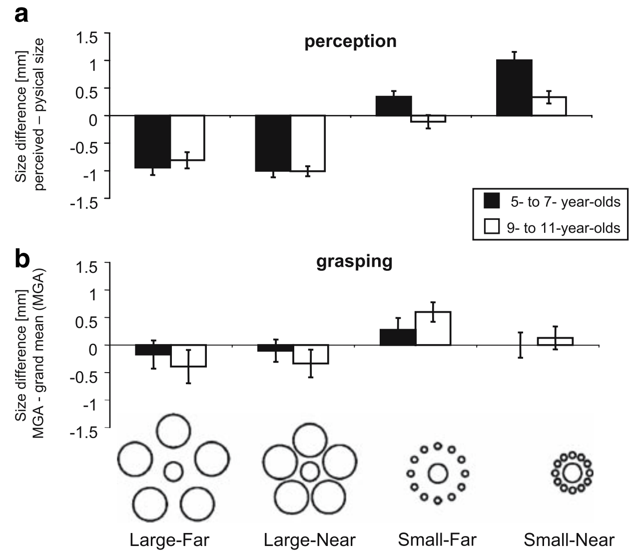

Fig. 3 Illusion effects on perception (**a**) and grasping (**b**) for the 5- to 7-year-olds (*black bars*) and the 9- to 11-year-olds (*white bars*) for the four illusion conditions. Illusion effects are pooled across the three different target sizes: **a** For the perceptual illusion effect the mean difference between the perceived size of the target disc and its physical size is shown. **b** For the grasping illusion effect the mean difference between MGA and the grand mean of the MGA is shown. The grand mean of the MGA was calculated separately for the two age groups. *Error bars* depict ± one standard error of the mean

the fact that the perceived size in some conditions does not differ from the actual size (e.g., for the 9- to 11-year olds in the Small-Far condition), does not necessarily imply that there was no illusion effect per se. This could be due to a general shift in the baseline, as it is frequently observed in this type of research (e.g., Pressey 1977). For our study only the difference between the illusion conditions (e.g., between Small-Far and Large-Near) is relevant.

Illusion effect on grasping

The MGA served as the dependent variable in a repeated measure ANOVA with the factors context-size (Small, Large), context-distance (Near, Far), target-size (28, 30, and 32 mm), and age (5- to 7- and 9- to 11-year-olds). Figures 3b and 4 show the main results of this analysis.

A significant main effect of context-size, $F(1, 37) = 8.84$, $P = 0.005$, revealed that children produced a larger MGA when grasping for target discs which were surrounded by small circles than for target discs which were surrounded by large circles. A main effect of target-size, $F(2, 74) = 49.63$, $P < 0.001$, showed the MGA to increase with increasing size of the target disc. No effect for context-distance was observed, $F(1, 37) < 1$, $P = 0.46$. Thus, children's MGA did not differ significantly between the Near and Far conditions. The interaction of age and context-size did not reach significance, $F(1, 37) = 1.81$, $P = 0.187$, and

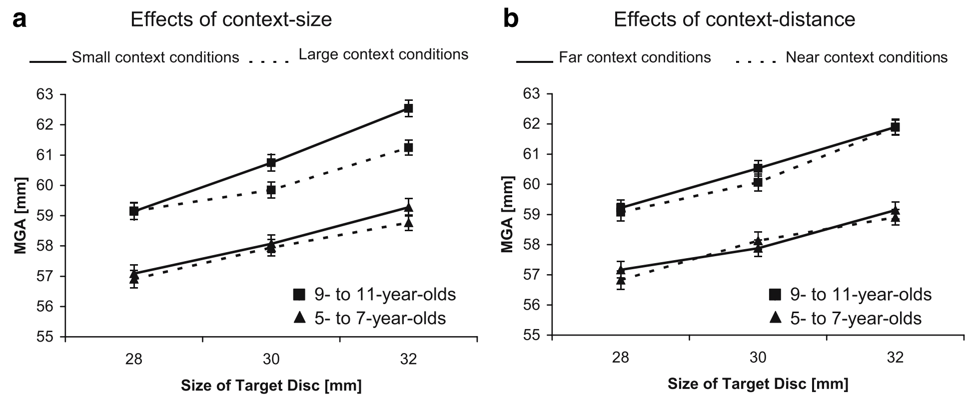

Fig. 4 Effects of the Ebbinghaus illusion on children's grasping: **a** The mean MGA is shown for the three target discs and the illusion conditions with small and large *context circles*. **b** The mean MGA is depicted for the three target discs against the Near and Far illusion conditions. *Error bars* depict ± one standard error of the mean

no other significant differences were observed (all P's > 0.149). However, performing the same analysis separately for the two age groups revealed that a significant main effect of context-size was apparent only in the group of the 9- to 11-year-olds, $F(1, 19) = 9.42$, $P = 0.006$, whereas 5- to 7-year-olds' grasping did not differ significantly between the Small and Large illusion conditions, $F(1, 18) = 1.32$, $P = 0.267$. In both age groups the main effect of target-size was significant (5- to 7-year-olds: $F(2, 36) = 14.45$, $P < 0.001$; 9- to 11-year-olds: $F(2, 38) = 42.05$, $P < 0.001$) and no further significant effects or interactions were observed (all P's > 0.18).

Thus the overall group of our study showed a positive grasping effect. This overall positive effect is due to the fact that the large majority of participants showed a positive effect and only a small number of participants showed a negative effect (see Fig. 5).

Comparison of perceptual- and grasping-effects

In order to compare the illusion effects on perception and grasping, we have to consider that a change in the physical size of an object might be reflected in the perceptual response differently than in the motor response. For example, a change of 1 mm in the physical size of an object might affect a perceptual judgment by 1 mm, whereas in a motor task the MGA might change only by, say, 0.8 mm (cf. Smeets and Brenner 1999). If those differences in the relationship between the response modes are apparent in responses due to physical size changes, they must also be expected in responses due to illusionary size changes. Ignoring those differences would lead to a misjudgment of the relationship between the perceptual and motor effects. In the example above this would mean that the motor effects are judged by 20% too low compared to the perceptual effects.

In our study children's perceptual judgments were related to a change in the physical size of the disc with a slope of 1.03 (*SEM* 0.03), while their MGA was related to a change in the physical size with a slope of 0.59 (*SEM* 0.06). As these slopes were quite different, we corrected for those differences by dividing the illusion effects by the slopes (Franz 2003; Franz et al. 2001, 2005; Glover and Dixon 2002).

We computed the mean corrected illusion effects for 5- to 7- and 9- to 11-year-old children of our study and for

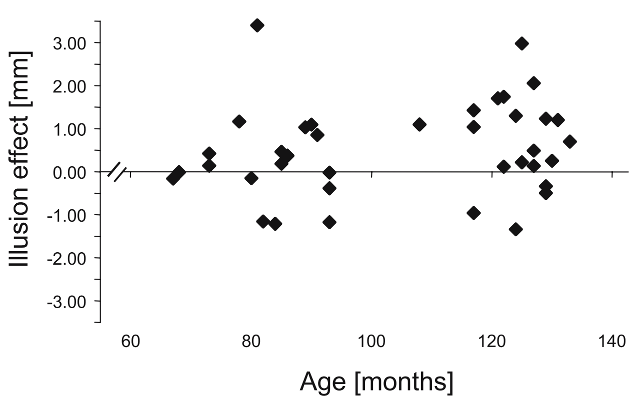

Fig. 5 Individual grasp effects as a function of age. For each participant the difference of MGA between the Small (pooled across the Near and Far conditions) and the Large (pooled across the Near and Far conditions) illusion contexts is shown

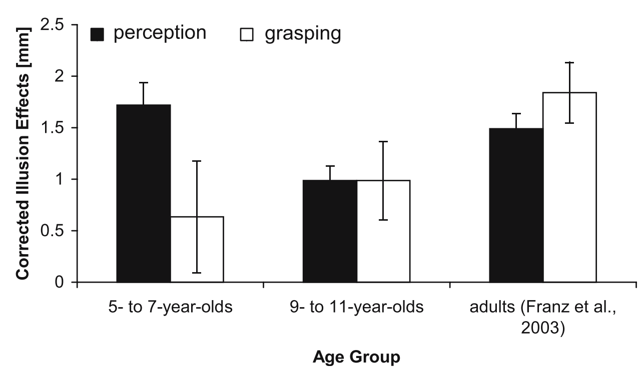

Fig. 6 Corrected illusion effects for perception and grasping. For each age group the mean corrected illusion effect (pooled across the individuals' mean illusion effects) is shown. *Error bars* depict ± one standard error of the mean

Table 1 Means (SD) of children's kinematic grasping parameters

	Age	
	5- to 7-Year-olds ($N = 19$)	9- to 11-Year-olds ($N = 20$)
Total movement time (ms)	560 (74.22)	512 (85.21)
Relative position of MGA (% of movement duration)	78 (5.53)	75 (7.21)
Mean MGA (mm)	58 (4.06)	60 (6.03)
Estimated maximum finger span (mm)[a]	115 (3.74)	134 (2.76)
Mean relative MGA (% of maximum finger span)	51 (3.49)	45 (4.18)
Absolute safety margin (mm)	28 (4.06)	30 (6.03)

MGA maximum grip aperture

[a] The estimation of the maximum finger span is based on a regression analysis of data provided by Kuhtz-Buschbeck et al. (1998)

comparison also reanalyzed data of adults from the Franz et al.'s (2003) study. For this, we pooled the adult data of Franz et al. in the same way as the children data and applied the same method of slope-correction to those data. Note, however, that adults in this study had no vision during grasping (open-loop condition), whereas children had full vision during grasping in our study (close-loop condition), so that this comparison can only be tentative. The corrected illusion effects for 5- to 7- and 9- to 11-year-olds and adults are shown in Fig. 6. The children's corrected illusion effects were submitted to an ANOVA of age (5- to 7- and 9- to 11-year-olds) and task (perception, grasping). There was a highly significant overall effect of the illusion, $F(1, 37) = 42.761$, $P < 0.001$, but no differential effects: neither the main effects of age, $F(1, 37) = 0.65$, $P = 0.43$, or task, $F(1, 37) = 2.41$, $P = 0.13$, nor the interaction of age and task, $F(1, 37) = 2.82$, $P = 0.10$, were significant. Also for the reanalyzed adults data there was an overall effect of the illusion, $F(1, 51) = 92.90$, $P < 0.001$, and no significant differences between the perceptual and grasping effects, $F(1, 51) = 1.26$, $P = 0.267$.

Kinematic grasping parameters

Grasping trajectories were analyzed with respect to developmental trends in the total movement time, the relative timing of MGA, the mean MGA across all disc sizes and the safety margin, which is defined as the absolute difference between MGA and size of the target disc. These results are summarized in Table 1. The analysis of total movement time revealed a trend toward faster movement in older children than in younger children. Five- to seven-year-olds needed on average 561 ms to grasp the target, whereas 10-year-olds performed the grasp within 512 ms. This difference just failed to reach the level of significance ($t = 1.89$, $P = 0.067$).

The timing of the MGA did not differ significantly between the two age groups. Five- to seven-year-olds reached their MGA at 78% of the movement duration and 9- to 11-year-olds did so at 75% of their movement duration ($t = 1.44$, $P = 0.159$).

The absolute mean MGA across all disc sizes was slightly, but not significantly smaller for younger (58 mm) than for older children (60 mm) ($t = -1.47$, $P = 0.149$).

The absolute safety margin increased from 5- to 7- to 9- to 11-year-olds by about 2 mm, but this difference failed to reach significance ($t = -1.47$, $P = 0.149$).

Discussion

The aim of the present study was to investigate the effects of the Ebbinghaus illusion under vision-for-perception and vision-for-action conditions and to test for possible explanations of the negative illusion effect found for grasping in a study conducted by Hanisch et al. (2001). In the following paragraphs we will discuss the results for each of the different conditions successively and consider their developmental implications.

Illusion effect on perception

In the perceptual condition, we observed the classical effect of the Ebbinghaus illusion for 5- to 7- and 9- to 11-year-olds. Discs surrounded by an annulus of small circles were perceived larger than discs surrounded by an annulus of large circles. Our observation that already children show this typical illusion effect in their perception corresponds to the findings of prior studies (Hanisch et al. 2001; Káldy and Kovács 2003; Weintraub 1979; Zanuttini 1996). Additionally, the magnitude of the illusion effect was within a similar range as the illusion effect found in adults using the same stimuli (Franz et al. 2003) (see Fig. 6). However, we also found a decrease in the magnitude of the illusion effect with age. This result does not fit well with previous observations of an increasing illusion effect with age during childhood (Káldy and Kovács 2003; Weintraub 1979; Zanuttini 1996). The absolute magnitude of the 5- to 7-year-olds illusion effect (1.7 mm) corresponds perfectly to adults' data in similar experimental settings (cf. Franz et al. 2003, Fig. 5) whereas 9- to 11-year-olds' illusion effect (about 1.00 mm) was a little smaller. In view of the numerous reports of increasing illusion effects during childhood, and in view of observing such an increase between 9- to 11-year-olds and adults only, the magnitude of the 5- to 7-year-olds illusion effect should be interpreted cautiously. Possibly in this age group the observed illusion effect overshot the actual illusion effect. This interpretation would reconcile the results of our study with the findings of the previous studies on children's perceptual illusion effects. There is no obvious explanation what would have caused the 5- to 7-year-olds to produce such a large illusion effect in our study and it only can be speculated that possibly aspects of motivation and concentration might have attributed to it. Thus, in our view, this effect might not necessarily reflect a general developmental trend toward a lower illusion effect in later childhood (at least as long as it is not replicated in other studies).

An interesting additional result concerning influences of the task setting on the perception of the illusion is the obtained main effect for context-distance: the closer the annuli were located around the target disc, the larger the target disc was perceived. This replicates findings of Massaro and Anderson (1971) and of Girgus et al. (1972). Moreover, the factor context-distance affected the illusion effect more in illusion conditions with small context circles than in illusion conditions with large context circles. A similar, albeit non-significant effect is apparent in data by Franz et al. (2003) and by Massaro and Anderson (see the slopes of the small and large context circles in Fig. 3 of Massaro and Anderson 1971).

Illusion effect on grasping

As already pointed out, one aim of the present study was to find an explanation of the negative illusion effect found by Hanisch et al. (2001). However, we failed to replicate this somewhat unexpected pattern in children's grasping. Instead, we observed a positive illusion effect on grasping, corresponding to the effect found in the perception condition: children grasped discs surrounded by an annulus of large circles with a smaller MGA than discs surrounded by an annulus of small circles. The absence of the negative illusion effect speaks against the idea that children adjusted their MGA to the overall size of the illusion context. Such an adjustment would have led to a larger MGA for the Large illusion conditions than for the Small illusion conditions and also to a larger MGA for the Far as compared to the Near conditions. In contrast, we observed neither a difference in MGA between Large and Small nor between Near and Far conditions.

The lack of a negative illusion effect, however, still does not rule out the possibility of an obstacle avoidance mechanism in form of a grip adjustment to the gap size of the illusion conditions. However, based on two findings we can rule this mechanism in our experiment as well. First, the differences in the size of the gap between the Near and the Far conditions did not lead to any differences in children's grasping. Second, we obtained significant differences in grasping between illusion conditions with constant gap size (Small-Near versus Large-Near or Small-Far versus Large-Far). Thus, the present findings do not appear to be modulated by adaptations to these aspects of spatial arrangement of the stimulus configurations.

While the overall analysis including both age-groups revealed no interaction between context-size and age, indicating that the overall grasping patterns were similar across age-groups, separate analyses for each age group yielded a significant effect of context-size only for the 9- to 11-year olds. In case of the 5- to 7-year-olds, the differences in MGA between the Small and Large illusion conditions failed to reach significance. This result can on the one hand be interpreted as resulting from a larger variability in younger children's grasping, combined with a relatively small number of trials we were able to measure, due to the young age. On the other hand, these results can also be interpreted as indication that the susceptibility of grasping to the Ebbinghaus illusion is just developing between 5 and 9 years of age.

Comparison of perceptual- and grasping-effects

As the most important result, we found that during childhood, and in 9- to 11-year-olds in particular, the illusion effects on perception and grasping are equally directed. That is, discs judged to be larger were grasped with a larger grip aperture, and vice versa. This result is in line with a series of studies that have yielded similar result in adults (Franz et al. 2000, 2003; Pavani et al. 1999). The statistical analysis of the grasping and perception effects provided no evidence of a dissociation of a vision-for-action-system and a vision-for-perception-system for neither age group. However, even though the grasping and perceptual effects did not differ statistically, the grasping effects seemed to be smaller than the perceptual effects for the 5- to 7-year-olds. This could be explained by assuming that either the perceptual illusion effects were relatively large or the motor effects were relatively small (cf. Illusion Effects on Perception in the Discussion section). Alternatively it could be assumed, that the illusion effects are different at younger ages and develop toward equal effects with increasing age. The age between 5 and 7 years might then mark a transitional phase in development, in which the difference between the illusion effects is progressively attenuated due to an increasing cross-talk between the dorsal and ventral pathway. Given that we found a marginal age-related increase in the illusion effect on grasping, but a decreasing effect in the perception condition, it would be plausible to assume that this cross-talk might be characterized by a process by which information processed by the vision-for-perception system becomes available to motor processes. However, as the analysis revealed no interaction effect of age and task, this interpretation remains speculative, and further research, maybe with younger children, is needed.

Our major result on the development of illusion effects on children's grasping differed clearly from the result described by Hanisch et al. (2001): while Hanisch et al. (2001) found a large negative illusion effect in grasping of 5- to 7-year-olds, we found a clearly positive illusion effect for this age-group. Before discussing potential sources of these differences we should first rule out that children in the present study showed an atypical grasping behavior per se.

Comparison of grasping kinematics

In order to evaluate whether children in our study grasped normally we compared the results of the grasping kinematics of our study to other studies on children's grasping (without illusions). The main studies we used as reference are the studies by Kuhtz-Buschbeck et al. (1998), Olivier et al. (2007), and by Zoia et al. (2006). These studies investigated 4- to 12-year-olds grasping (Kuhtz-Buschbeck et al. Olivier et al.) and 5-year-olds and adults grasping (Zoia et al.) to cylindrical or rectangular objects and performed detailed analyses of the kinematic parameters.

First, we compared movement time across the four studies. In all studies a decline in movement time between younger and older children and between children and adults was observed. As this decline between 4- and 12-year-olds in Kuhtz-Buschbeck et al.'s (1998) study and between 5- to 7- and 9- to 11-year-olds in our study missed significance marginally, this might indicate that children's grasping kinematics are developed quite far at the age of 5–7 years and that the rather small movement time reduction in the following years mirrors fine tuning in children's prehension. Thus, concerning movement time, the findings of the present study parallel those found by Kuhtz-Buschbeck et al. Olivier et al. (2007), and by Zoia et al. (2006).

Next, we compared the MGA. Our results indicate that with increasing age children used a larger absolute MGA. Similar Zoia et al. (2006) observed an increase in absolute MGA between 5-year-olds and adults. A direct comparison of these results with the result of Kuhtz-Buschbeck et al. (1998) is limited due to the fact that in their experiment the objects were scaled according to the children's maximum finger span, whereas in our study the size of the objects was constant for all participants. Therefore, we performed a post hoc analysis with our data to determine the size of the normalized grip aperture, a measure that is also provided in the study by Kuhtz-Buschbeck et al. and also by Zoia et al. For this analysis we used an estimate of the maximum finger span based on Kuhtz-Buschbeck et al.'s data (see Method section). The normalized grip aperture calculates as the MGA relative to the children's maximum finger span. We found that in our study the mean MGA of the 5- to 7-year-olds had a size of 53% of their maximum finger span, significantly more than 9- to 11-year-olds, who only used 46% of their maximum finger span for their MGA, $t = 5.18$, $P < 0.001$. This result is in line with findings of a significant decrease of the normalized grip aperture between 4- and 12-year-olds by Kuhtz-Buschbeck et al. as well as with the finding of a decreasing normalized MGA between 5-year-olds and adults by Zoia et al. When we consider hand growth between 5 and 11 years of age such a development might be expected. Olivier et al. (2007), also describe a decrease of relative MGA with age, however in this case relative refers to object size and not to the maximum finger span. As object size was constant for all their participants they in fact observed a decline of absolute MGA with age. In contrast to ours and the other two studies (Kuhtz-Buschbeck et al. Zoia et al.) the grasp objects in Olivier et al.'s study were clearly larger (75 mm) and Olivier et al. themselves suggest a ceiling effect for 6-year-olds' grasping. Therefore a comparison of Olivier et al.'s and our result on this aspect seems problematic.

Finally, concerning movement timing, we observed that children reached their MGA at around 75–78% of movement duration. Kuhtz-Buschbeck et al. (1998), Olivier et al. (2007), and Zoia et al. (2006) also observed that children's MGA timing was well within the second half of the grasp, a similar timing was described for adults (Smeets and Brenner 1999) as well. Note that there is a certain controversy whether MGA timing is accomplished later or earlier with increasing age (Kuhtz-Buschbeck et al. versus Olivier et al. and Zoia et al.). However, as we observed no statistical differences between 5- to 7 and 9- to 11-year-olds MGA timing we are not in a position to take a stand within this debate. Overall, our observations on the kinematic grasping parameters are very similar to Kuhtz-Buschbeck et al.'s and Zoia et al.'s findings, and in many aspects also to Olivier et al.'s findings, indicating that we observed normal grasping kinematics.

So what might have led to the differences between the results of Hanisch et al.'s (2001) and our study? One possibility to account for the different outcomes is to consider methodological differences between the two studies. Therefore, it seems important to scrutinize all the methodological differences that are present between the studies.

Methodological aspects

Methodological differences between Hanisch et al.'s (2001) and our study were present in the appearance of the stimuli-disks and context circles and in how they were presented. In our study the disks and circles had a white surface and a black outline, whereas in Hanisch et al.'s study stimulus had a yellow surface, a black outline, and a smiling face at their center. The second methodological difference concerns the experimental setup. While in our study children sat on a chair and the viewing distance was constant for all participants, in Hanisch et al.'s study the stimuli were placed on a table, the height of which was adjusted to the participant's arm length and participants stood while watching and grasping them. Thus the viewing distance depended upon the arm length, leading to a larger viewing distance for adults as compared to children. For both these differences we do not see an obvious reason why these should cause such different outcomes. Another methodological difference which might be a more promising reason for the different results concerns the arrangement of the stimuli. In our study there was always only a single illusion figure visible for the participants. In contrast in Hanisch et al.'s study two Ebbinghaus-figures (one with large context circles and one with small context circles) were presented next to each other. Participants viewed the stimuli while not knowing which of the two central disks they will have to grasp. After this previewing period the experimenter told them which disc to grasp. It might be that during that preview period a different movement plan was generated, which might have interfered later with the final movement plan which was generated at the time when the grasping goal was named by the experimenter. Thus, the reversal of the illusion effect in grasping could be based on interferences of the movement plans resulting from the presence of two illusion figures. Currently, we do not know whether this is a feasible assumption that can explain the different outcomes. To clarify this question, it would be necessary to compare both paradigms in a single study with the same participants. It will therefore be an exciting task for future research to show whether it is possible to change the effect of the Ebbinghaus illusion on the grasping of children by manipulation of the stimulus presentation.

Conclusion

As one of the main results we did not find a negative illusion effect in children's grasping. Thus the Ebbinghaus-Illusion does not deceive children's grasping reversely than their perception in general. In contrast, the results revealed that already during childhood, in 9- to 11-year-olds in particular, perception and grasping are deceived by the illusion in the same direction. A similar observation has been reported for another geometrical visual illusion, the Müller-Lyer illusion. Gentilucci et al. (2001) observed that 7- to 8-year-olds like adults were deceived by the Müller-Lyer illusion in a drawing task (interpreted as perception), as well as in a pointing task (interpreted as action). However, Gentilucci et al. observed differences between children and adults concerning arm kinematics in a pointing task. When pointing was executed under full vision children produced longer movement times, larger arm peak velocities and reached the arm peak velocity later than adults. These age differences in pointing kinematics were specific to the reaction on the Müller-Lyer illusion and were not present in pointing outside of illusion contexts (Kuhtz-Buschbeck et al. 1998). In our study however no age differences that can be specifically ascribed to responses on illusion contexts were observed. Movement time decreased with age in our study as well as in Kuhtz-Buschbeck et al.'s (1998), Olivier et al.'s (2007) and Zoia et al.'s (2006) studies and MGA timing within illusion contexts was very similar for children (75–78%) and adults (76%, Franz et al. 2005) and moreover very similar to MGA timing outside of illusion contexts (Jeannerod 1984; Kuhtz-Buschbeck et al. 1998; Olivier et al. 2007; Smeets and Brenner 1999; Zoia 2006). Thus, we could not find illusion-specific age differences in kinematic parameters of grasping. Instead, the large similarities between the development of children's prehension within and outside of illusion contexts support in our view the validity of our overall findings.

Further, our results showed that by the age of 9–11 years the illusion effects on perception and grasping were equally strong. Therefore, our result supports the idea that in adults and later childhood the perceptual- and the grasping-illusion-effects are based on common mechanisms. For younger children our results are not quite as apparent. They could be compatible both, with the idea that illusion effects on grasping develop later than illusion effects on perception, and the idea that the illusion effects on grasping are similar to the perceptual effects—even for young children. It is a task for further studies to investigate these alternatives in detail.

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