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Interaction between perceptual and motor magnitudes in early childhood

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ABSTRACT

Recent research has suggested that all types of size-related information are linked by a generalised system that codes for domain-independent magnitudes. This generalized system is further suggested to be acquired through everyday sensorimotor experiences with contingencies of size-related information in the real world. The aim of the present study was to investigate the existence of this common representation and its impact on the coupling of perception and action in early childhood. According to an embodied view on magnitude representation, an association between perceived magnitude information and size-related motor features, such as applied motor force, should emerge as soon as motor control is sufficiently developed. This hypothesis was tested in 2.5- to 3-year-old toddlers by engaging them in a computer game-like experimental task in which they were required to move objects placed on a platform upwards by pressing a button. The amount of objects was varied systematically (small amount: 3 vs. large amount: 15) and the force children applied on the button while moving the objects was recorded. Importantly, the amount of applied force was not relevant for successfully playing the game. The analysis of the peak force revealed that motor responses were executed more forcefully when children were presented with a large amount of objects compared to a small amount, irrespective of the toddler's motor abilities which were evaluated by two additional measures (force control and general fine motor skills). This general effect of perceived magnitude information on the task-irrelevant applied motor force confirms our notion that a link between perceptual and motor magnitudes exists already in early childhood and provides new evidence for a sensorimotor grounding of magnitude concepts.

1. Introduction

Dealing with magnitudes is an integral part of everyday life. How does our brain process magnitude information? It has recently been speculated that, for instance, numerical magnitude information becomes meaningful only when it can be mapped to concrete

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bodily experiences with size in daily life (Andres, Olivier, & Badets, 2008; Lindemann, Rueschemeyer, & Bekkering, 2009). This notion of embodied cognition (Wilson, 2002) holds that each semantic concept is grounded in basic sensorimotor representations and is therefore closely linked to low-level perceptual and motor codes (Barsalou, 2008; Glenberg & Kaschak, 2002; Fischer & Zwaan, 2006). In line with this view, it has been argued by several authors that the brain does not process magnitudes of different domains by separate specialised structures, but that different magnitudes are rather represented by shared common cognitive codes (Walsh, 2003; Hommel, Müsseler, Aschersleben & Prinz, 2001). The model of analogue magnitude representations of Walsh (2003), for instance, assumes that all magnitude information is coded together within a shared system, often referred to as the *generalised magnitude system*.

While research on perception-action coupling has a rather long tradition and therefore provides a large body of evidence for the general existence of shared common codes between these two domains (for a recent review see for instance, Hommel, 2013), evidence that magnitude information, in particular, is coded within the same representational medium is, however, still rather limited. Behavioural support for shared magnitude codes comes, for instance, from behavioural studies in adults showing interferences between different perceived magnitudes, such as temporal duration and space (Xuan, Zhang, He, & Chen, 2007; De Long, 1981; Mitchell & Davis, 1987) or luminance (Xuan et al., 2007), the numerical and the physical size of number symbols (e.g., Tzelgov, Meyer, & Henik, 1992) and objects (Badets, Andres, Di Luca, & Pesenti, 2007), or the numerical size and the perceived amount or strength of tactile stimulation (Krause, Bekkering, & Lindemann, 2013). Interestingly, semantic numerical magnitude representations have also been shown to be linked to magnitude-related motor codes, as for example, reflected by the interference between numbers and the aperture size during object grasping (Lindemann, Abolafia, Girardi, & Bekkering, 2007; Andres, Ostry, Nicol, & Paus, 2008).

Further evidence for shared cognitive magnitude codes in semantic number processing and motor planning is coming from a recent study of Vierck and Kiesel (2010) on the production of response force during number classifications. Adult participants had to indicate the parity of single Arabic digits between 2 and 9 by producing either a weak or a forceful button press response using the index finger of their preferred hand. After analysis of the reaction times and error rates for each type of response towards all numbers, the authors observed a linear relation between response times or error rates and numerical size, with faster and more accurate weak responses for small numbers compared to large numbers and faster and more accurate forceful responses for large numbers compared to small numbers. These results have been interpreted as an indication for a link between numerical and motor magnitudes (i.e., motor force) in adult participants. However, numerical size had no direct influence on the actually produced response force itself, as revealed by an additional analysis on the maximally applied response fore (peak response force). That is, larger numbers did not induce stronger responses than smaller numbers.

Similarly, a lack of influence of numerical size on response force has also been reported by Fischer and Miller (2008). In this experiment, adult participants had to indicate the parity of a number by a left or right button press response. While the numerical size affected reaction times depending on the congruency between numerical size and the side of response – i.e., faster left responses for small numbers and faster right responses for large numbers (so-called SNARC effect; Dehaene, Bossini, & Giraux, 1993) – peak response force was not modulated by numerical size. Interestingly, in contrast to symbolic magnitude information, non-symbolic perceptual magnitudes have been shown to affect the applied force of button press responses in adults. For instance, Jáskowski and Włodarczyk (2005, 2006) showed that the loudness of an auditory stimulus as well as the brightness of a visual stimulus have a direct influence on the peak response force, with louder and brighter stimuli leading to stronger responses. These results clearly demonstrate the impact of a generalised magnitude representation on the coupling of perception and motor control in adults.

Although the coupling between perception and action has been central to the investigation of motor skill development in infancy and early childhood (see Adolph & Berger, 2006 for a review), showing a mutual dependence of especially manual motor behaviours such as reaching and grasping on the action-perception coupling (von Hofsten, 2003), little is known about the relation between the perception of magnitude and magnitude-related aspects in motor control in young children. The aim of the present study was therefore to investigate the development of shared magnitude representations and their impact on the coupling of perception and action.

Here, we argue that an embodied view on shared magnitude representations implies that a concept of abstract domain-independent magnitudes is derived through early bodily experiences. If information about magnitude indeed becomes meaningful only when it can be mapped to concrete bodily experiences with size in daily life (c.f. Andres, Olivier et al., 2008; Lindemann et al., 2009), then the development of magnitude representations in early childhood should be based, to some extent, on sensorimotor-related size information that are relevant for action. Consequently, a coupling between perceived magnitude and size-related motor features, such as response force, should be observable already from early on in life. Moreover, such a direct perception-action coupling in the magnitude domain should manifest itself not only indirectly when response force is relevant for the task (cf. Krause, Lindemann, Toni, & Bekkering, 2014; Vierck & Kiesel, 2010). Instead, we predict that perceived magnitude information has a direct and automatic impact on the production of response force itself, irrespective of task-relevance. That is, if perceptual and motor magnitudes are linked by a common representation, then the perception of a large amount compared to a small amount should lead to more forceful responses, even when the extent of applied response force is irrelevant for a given task.

The present study tested the hypothesis of a link between perceptual and motor magnitudes in 2.5- to 3-year-old toddlers. It is around this age that the increasing integration of gross and fine motor skills allows the execution of more complex actions such as, for instance, throwing a ball (Meisels, Marsden, Dombro, Weston, & Jewkes, 2003) or building a tower of building blocks (Bullock & Lütkenhaus, 1988). While infants during their first year of life significantly improve in regulating the force they apply (e.g., when banging with a toy hammer; Kahrs, Jung, & Lockman, 2012), it is only by the age of 2.5–3 years that young children show stable (adult-like) kinematic motor patterns in goal-directed multi-joint coordination (Konczak & Dichgans, 1997) and have developed a complex motivational system for mastering and completing tasks (Jennings, 2004), allowing them to successfully perform goal-directed actions with respect to externally determined task demands (Bullock & Lütkenhaus, 1988). Both, the regulation of force in manual goal-directed actions and the capacity to repetitively execute a task were crucial requirements for the current investigation.

To examine whether children exhibit a coupling between perceived magnitude and motor force, we engaged them in a computer-based play situation in which two different numbers of food objects (small: 3 vs. large: 15) had to be moved to the top of the display by pressing a force-sensitive response button. We hypothesised that – even though the extent of applied force was entirely irrelevant for the task – a large amount of objects would lead to stronger responses compared to a small amount of objects. We furthermore expected the effect of perceived magnitude on motor force production to be modulated by experience with force control. In particular, if an interaction between perceptual and motor magnitudes exists already in early childhood, the effect of perceived magnitude on motor force production should be measurable as soon as children have the necessary means to comply with the motor demands of the experimental task. The absence of such an effect even in children that do have the necessary motor skills, on the other hand, would argue against our hypothesis and rather suggest that perceptual and motor magnitudes become associated only later during development. We therefore additionally examined the children's general fine motor skills as well as their capability to voluntarily produce different degrees of force in our specific setting.

2. Method

2.1. Participants

A total of 30 young children (11 female) between 29 and 36 months of age (mean = 31.30, SD = 2.58) were tested. The sample size was chosen based on our review of related research on force control (e.g. Kahrs et al., 2012) and magnitude processing in young children (e.g. Lourenco & Longo, 2010). All children were recruited from a database of families who volunteered to participate in developmental studies, and they were accompanied to the testing session by a parent who gave written consent for participation of his or her child in the experiment. Participants predominantly came from middle to upper middle class families who were recruited through birth records from a medium-sized city in Europe.

2.2. Setup

The toddlers were seated on the lap of the parent in front of a table with a computer display (viewing distance approximately 60 cm) and a custom-made response button (see Fig. 1a), which recorded the applied motor force. The experimenter was seated next to the toddler. The force-sensitive response button measured forces up to 3304 Centi-Newtons (cN) with an approximate resolution of 13 cN each 16 ms. The experiment and the force recordings were controlled using the open-source software *Expyriment* (Krause & Lindemann, 2014). During the entire experiment, the toddlers' performance was video recorded.

2.3. Material

Two computer game-like scenarios were developed. Stimuli were always presented in front of a light blue background. In the experimental task, the perceptual magnitude was manipulated by the number of presented objects. That is, visual stimuli consisted of coloured drawn pictures of 5 different food objects (apples, croissants, donuts, popsicles, and pears) in sets of either 3 (small amount) or 15 items (large amount) of the same type and size (width = 0.91°, height = 0.91°), stacked into a pyramidal shape on top of a drawn horizontally oriented black platform (width = 15.94°, height = 0.48°; see Fig. 1b). The size of the objects was kept constant, resulting in a visually larger pyramidal heap for 15 items compared to 3 items. Since both numerical and physical sizes are conceived as instances of perceptual magnitudes, the study refrained from controlling the correlation between these two visual features to ensure a parsimonious design appropriate for few experimental trials. Auditory stimuli, which were included as a motivating feedback to keep children engaged in the task, comprised 10 different animal sounds (donkey, sheep, cock, owl, frog, cat, cow, dog,

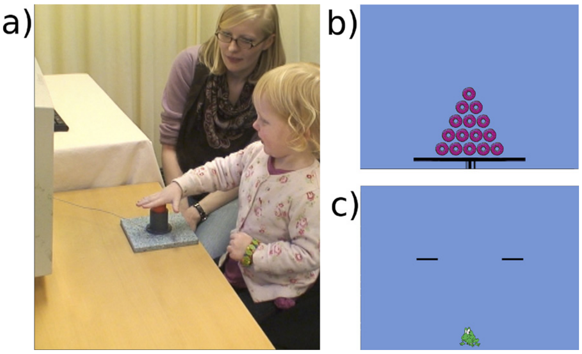

Fig. 1. a) The experimental setup. Children were sitting on their parent’s lap in front of a table with a computer display and a response button. The experimenter was seated next to the child. **b)** The experimental task. An example of a 'large amount' condition trial. Pressing the response button made the platform move to the top of the display with constant speed as long as the button was pressed. **c)** The test of force control. An example of a 'high' condition trial. The frog had to be positioned in between the two black bars by controlling the force applied to the response button.

bird, and horse).

In the test of force control, visual stimuli consisted of a green cartoon frog (width = 2.86°, height = 2.86°) and two black horizontal bars (width = 2.96°, height = 0.29°; distance = 8.96°) at two different vertical positions (distance to bottom of display: low = 4.77°, high = 12.84°; see Fig. 1c). A fanfare sound was used as auditory feedback.

2.4. Procedure

Each child was assigned to one of two task orders. At the beginning of each task, the experimenter gave an oral explanation as well as a practical demonstration of the computer game to the child.

In the experimental task, food objects placed on a horizontally oriented platform had to be moved upwards until they had disappeared from the upper edge of the display (travel distance = 21.61°) to an imaginary (i.e. not visible) animal, by pressing the response button. The platform moved upwards with a constant speed as long as the button was pressed with a certain minimum force (63 cN). Force was task-irrelevant and pressing the button more strongly did not affect the procedure. A new trial started when the response button was released. If the platform reached the top of the display (after 3000 ms) before button release, an animal sound was played to the toddlers as motivational feedback.

In the test of force control, the frog had to be moved vertically to a position marked by the two black horizontal bars on the screen. In contrast to the experimental phase, the extent of applied force was relevant to this task. The position of the frog could be controlled continuously by applying different amounts of pressure on the response button. That is, for every moment in time, the harder the button was pressed at this moment, the higher the position of the frog on the screen. Children were instructed to control the pressure on the button in such a way that the frog would reach the marked position. A match between the marked position and the frog's position was indicated by the two black bars changing their colour to green. When the child kept the requested force range (i.e. the frog stayed in the marked position) for more than 1500 ms, the trial ended successfully with an encouraging fanfare sound played to the child as feedback. If the frog did not reach the marked position after 90 s the attempt was rendered unsuccessful.

At the end of the testing session, each child's fine motor skills were assessed with 4 items from the Bayley Scales of Infant Development (Bayley, 1993; van der Meulen, Ruiter, Lutje Spelberg, & Smrkovsky, 2002): threading beads (88), grasping a pencil (90), drawing a circle (96) and (un)fastening a button (101).

2.5. Design

Experimental task and test of force control were blocked and the order was counter-balanced over participants. The experimental block consisted of 20 trials in total with 10 'small amount' condition trials and 10 large amount' condition trials. The 5 visual stimuli (food objects) and 10 auditory stimuli (animal sounds) were randomly paired with each trial. The presentation of the trials within the experimental block was randomised.

In the test of force control children were given maximally 20 attempts, half with the horizontal bars at the low position and half at the high position. The presentation of low and high horizontal bars was randomised.

2.6. Data analysis

Data was preprocessed in the programming language Python (Python Software Foundation, http://www.python.org). All analyses were done in R (R Core Team, 2014) using the packages 'ez' (Lawrence, 2015), 'afex' (Singmann, Bolker, & Westfall, 2015) and 'ltm' (Rizopoulos, 2017). Power analysis was performed using G*Power (Faul, Erdfelder, Buchner, & Lang, 2009).

2.6.1. Fine motor skills

To quantify the fine motor development of the children, we aggregated the data from the 4 motor items (beads threading, button (un)fastening, pencil grasping, and circle drawing) and calculated for those children who participated and co-operated in all 4 items (n = 20) the sum of successful items. These choices were motivated by the fact that not all children provided data for all 4 items, as well as our aim to capture general motor competence with this test, which is represented by a combination of items, rather than by a specific one.

2.6.2. Test of force control

Only trials were included during which the child was paying attention to the screen and operated the button without any help from the experimenter or parent, as assessed from the video recordings by an independent researcher. A reassessment of 6 random video recordings (~20% of the total data) by a second independent researcher yielded an agreement on included trials of 98.3%. The test of force control was considered to be successful if a child was able to voluntarily move the frog to each of the two marked positions (low and high) at least once without help from the experimenter or the parent. Given that the frog had to be held at the position for 1500 ms – a goal which could not be achieved by accident – the demonstration of one successful performance per level was a sufficient criterion. To compare the force control test with the fine motor skills, the point biserial correlation was calculated.

2.6.3. Experimental task

Only trials were included during which the child was paying attention to the screen and operated the button without any help from the experimenter or parent, as assessed from the video recordings by an independent researcher. A reassessment of 6 random video recordings ($\sim$20% of the total data) by a second independent researcher yielded an agreement on included trials of 98.1%. Furthermore, all trials in which children pressed the response button for longer than 200 ms were considered, which excluded anticipatory responses. Per trial only response force data within the first 3000 ms (i.e. until the food objects had moved completely out of the display) were analysed. To test a possible general influence of the type of food object used as visual stimuli on the children's response force, mean peak response force was calculated for each stimulus per participant and entered into a one-way repeated measures ANOVA with the factor Food Object (apples, croissants, donuts, popsicles, pears). To test our hypothesis of a stronger force production when children were responding to a large amount compared to a small amount of objects, we calculated the mean peak response force for each condition individually for all children, and performed a 2 × 2 × 2 repeated measures ANOVA with the within-subject factor Amount of Objects (small, large) and the between-subject factors Task Order (test of force control first, experimental task first) and Test of Force Control Performance (passed, not passed). To further verify whether differences in motor competence might help to explain a potential link between motor and perceptual magnitudes, the correlation between the sum of successfully performed/passed fine motor skill items and the difference in peak response force between conditions was calculated. The choice of peak response force as outcome measure in the current study was motivated by previous studies that investigated if/how peak response force interacts with other perceived magnitudes in adults (Vierck & Kiesel, 2010; Fischer & Miller, 2008; Jáskowski & Włodarczyk, 2005, 2006).

2.7. Open data

Raw data (except video recordings, due to data privacy protection) as well as experimental and analysis scripts are available via the Open Science Framework platform: https://osf.io/xn8cm.

3. Results

3.1. Fine motor skills

The distribution of fine motor skills scores and the performance on the different items are summarised in Tables 1 and 2. The majority of children passed at least three of the four items.

3.2. Test of force control

On average, children attempted to move the frog to the low position 2.47 times and 1.53 times to the high position. 18 children (60%) succeeded in the test. The point biserial correlation coefficient between the force control test (passed, not passed) and the summed fine motor scores was r_{pb} = -0.04, suggesting that the force control test measured a different aspect of motor development than items typically used to assess fine motor skills, and that it might be a more appropriate measure for the current study to asses children's experience with force control.

3.3. Experimental task

On average, children carried out 63.8% of all possible trials in the 'small amount' condition (12.77 trials; SD = 4.73) and 64.3% in the 'large amount' condition (12.87 trials; SD = 4.35), $|t|(29) < 1$. Children released the response button before the platform reached the top of the screen in 30.03% of the trials in the 'small amount' condition (3.83 trials; SD = 3.04) and in 28.50% of the trials in the 'large amount' condition (3.67 trials; SD = 3.18), $|t|(29) < 1$. The average button press duration was 3287 ms in the 'small amount' condition (SD = 663) and 3417 ms in the 'large amount' condition (SD = 792), $t(29) = 1.11$, $p = .28$, showing that children released the button on average 352 ms after the food objects disappeared at the top of the screen. Peak force was reached on average after 801 ms (SD = 347). This duration did not differ between the “small amount” (813 ms; SD = 378) and “large amount” condition (790 ms; SD = 319), $t(29) = 0.44$, $p = .66$.

The one-way repeated-measures ANOVA showed no main effect of Food Object, $F(4,116) < 1$, suggesting that children responded to all food objects with comparable force.

Most importantly, in accordance with our hypothesis, the 2 × 2 × 2 repeated measures ANOVA revealed a significant main effect of Amount of Objects, $F(1,26) = 4.35$, $p < .05$, $\eta_p^2 = 0.14$, with stronger responses in the 'large amount' condition (1931 cN, SD = 375), compared to the 'small amount' condition (1828 cN, SD = 359), showing a magnitude congruency (see Fig. 2). This effect did not reach significance in post-hoc repeated measures ANOVAs with the within-subject factor Amount of Objects (small, large) and the between-subject factor Test of Force Control Performance (passed, not passed) for the sub-groups of children who performed the

Table 1
Overview of children's overall performance on the fine motor skills items.

	Total score				
	0	1	2	3	4
Children (%)	0	10	5	65	20

Table 2
Overview of the success rate on the fine motor skills items.

	Threading Beads	(Un)fastening Button	Grasping Pencil	Drawing Circle
Success (%)	80	30	100	85

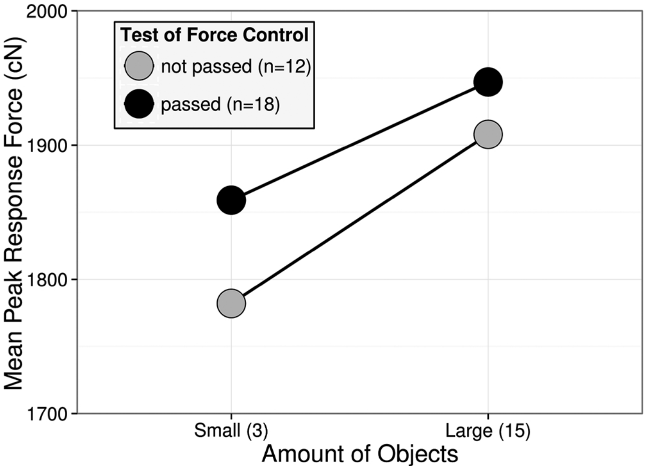

Fig. 2. The magnitude congruency effect. A large amount of food objects (15) led to a significantly higher peak response force compared to a small amount of food objects (3). The effect was not modulated by the performance in the test of force control.

test of force control first, $F(1,11) = 1.59, p = .23$, and those who performed the experimental task first, $F(1,15) = 3.02, p = .10$. The main effect of Task Order did not reach significance, $F(1,26) = 3.31$, $p = .081$, $\eta_p^2 = 0.11$, nor did the main effect of Test of Force Control Performance, $F(1,26) < 1$. There was also no significant interaction effect between the factors Amount of Objects and Task Order, $F(1,26) = 0.02$, $p = .89$, suggesting that the position of the test of force control (before or after the experimental task) did not influence the magnitude congruency effect. Power analysis indicated that given the a priori specifics of the current study (n = 30, two groups, two conditions, and an assumed correlation among repeated measures of 0.8) the power to detect such an interaction effect of medium size ($f = 0.25$) was 99%.

In contrast to our expectations, the interaction between the factors Amount of Objects and Test of Force Control Performance did not reach significance, $F(1, 26) < 1$, suggesting that there were no differences in the magnitude congruency between toddlers who passed the test of force control and those who did not (see also Fig. 2). However, there was a significant three-way interaction between the factors Amount of Objects, Task Order and Test of Force Control Performance, $F(1,26) = 5.14$, $p < .05$, $\eta_p^2 = 0.17$, which we did not attempt to interpret due to the unequal distribution of children who passed the test of force control and those who did not over the factor task order.

The correlation between the sum of successfully performed/passed fine motor skill items and the difference in peak response force between conditions was not significant, $r = 0.068$, $p = .78$.

4. Discussion

The current study provides evidence for an interaction between perceptual and motor magnitudes in early childhood and its impact on the coupling of perception and action. We show that changes in the amount of presented objects influence the peak response force produced by 2.5- to 3-year-old toddlers when pressing and holding a button during a gamified experimental task. We interpret our data as evidence for a magnitude congruency effect. In particular, the presence of 15 objects led to significantly stronger button press responses, compared to the presence of only 3 objects. This effect of perceptual magnitude on the motor force production emerged even though the amount of applied force was entirely irrelevant for the task. Interestingly, the effect was not modulated by differences in experience with force control, as determined by an additional test of force control.

The effect of perceptual amount on the production of motor force in toddlers is in line with the notion of shared representations between action and perception (Hommel et al., 2001) as well as with the notion of a generalised magnitude system, which suggests that different kinds of magnitude information from 'prothetic' (i.e. quantifiable) dimensions (Stevens, 1975) are represented together in the brain, irrespective of the domain or modality this information comes from (Walsh, 2003). Walsh's theory assumes that all magnitude information is processed by the same underlying mechanisms and consequently predicts an interaction of the processing of those magnitudes. The current study shows that visually presented magnitude information (i.e. amount of objects) has a direct impact on the intensity of a manual motor response (i.e. force). This interaction between perceptual and motor magnitudes strongly supports the hypothesis that both magnitudes share a common representation. While previous research already suggests a shared representation of perceived size information from different dimensions in young children (e.g. Lourenco & Longo, 2010; see also

Piaget, 1969, 1965; Siegler & Richards, 1979; Levin, 1979, 1977), our findings extend this previous literature into the motor domain and show that also motor magnitudes seem to be linked to magnitudes from other domains already in early childhood.

The present study is among the first to demonstrate a direct influence of perceptual magnitude information on force production in young children, when the amount of applied motor force is not relevant for the task. This finding provides new empirical evidence from toddlers' behaviour for the view of an embodied magnitude representation. The notion of embodied cognition states that abstract cognitive concepts, like magnitude, are grounded in sensorimotor experiences (Barsalou, 2008) and become meaningful by being coupled to bodily representations (Lindemann et al., 2009). Here we show that, already in early childhood, perceptual magnitude information is coupled with the concept of motor force. Our data might also be relevant for an ongoing debate in the field of numerical cognition, concerning the question of when a common magnitude representation develops. More specifically, there seems to be disagreement about whether domain-specific magnitude representations (such as numerical magnitude) develop first (Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004) and only later become connected to similar specialised magnitude representations of other domains, or whether a common magnitude representation is in place first (Walsh, 2003), and only later builds the basis for more domain-specific magnitude representations (for an overview of both views see Cohen Kadosh, Lammertyn, & Izard, 2008; Lourenco & Longo, 2011). Here, we show evidence for a shared representation of perceptual and motor magnitudes which is present already in 2.5- to 3-year-old toddlers. At that age children typically start showing stable reaching movements and we would thus expect children's arm movements to be controlled enough to reveal reliable effects in force production. Our demonstration of such an early influence of perceptual magnitudes on the motor magnitude of response force provides therefore evidence for the hypothesis that this shared sensory-motor magnitude representation is in place first and might precede other abstract or domain-specific magnitude representations.

The notion of an early shared representation of perceptual and motor magnitudes is also in line with other findings showing that children base judgements about magnitude in one domain on magnitude in other irrelevant domains (Stavy & Tirosh, 2000; Levin, 1977, 1979; Piaget, 1965, 1969; Siegler & Richards, 1979). Yet, potential prior experience of children with different magnitudes and their interrelations cannot entirely be ruled out, and hence neither can the alternative hypothesis. Future research on the interplay between the development of domain-specific and generalised magnitude representations is needed to provide a definite answer to this issue. Future research on the interplay between the development of domain-specific and generalised magnitude representations is needed to provide a definite answer to this issue.

Notably, the magnitude congruency effect in our study was (against our expectation) not modulated by the performance in the test of force control, which was thought to classify children with and without active experience with force control. We can think of two possible explanations for this result. It might indeed be the case that a coupling between perceptual and motor magnitudes is so fundamental that it is already present even before children have first active sensorimotor experiences with size (e.g. the processing of perceptual magnitudes and motor magnitudes might be hard-wired in the brain and hence present from birth on). An alternative explanation, however, might simply lie in the test of force control we used in the current study itself. To be more precise, it is very well possible that the test did not properly distinguish between children who could voluntarily control their force and those who could not. Since the passing criterion was a successful performance that entailed applying a certain force for 1500 ms in two different conditions (a criterion that cannot be reached by chance alone), it can be assumed that the group of children who passed the test of force control is a rather homogeneous group. Importantly, however, this assumption cannot be made for the group of children that did not pass the test, since an unsuccessful performance could also reflect a lack of motivation or willingness of the child to perform the task. It might thus be the case that the group of children that did not pass the test of force control also entails children who in principle do have the necessary experience with force control and therefore actually do show an effect in the experimental task. Notably, however, we also did not observe a correlation of fine motor skills with the performance in the experimental task. Future research on the development of force control in children is needed to further investigate the effect of experience with force control in more detail.

It is important to note that "amount" in our design is a possible composition of several magnitudes, namely numerosity (i.e. 3 vs. 15 objects), weight (i.e. 15 objects are heavier than 3 objects), and physical size (i.e. 15 objects will results in a bigger heap than 3 objects). Given the design of the current study it is not possible to attribute the magnitude congruity effect to any single one of those magnitudes alone. However, while it has been shown that young children rely predominantly on weight when solving balance scale problems by applying systematic hierarchical rules (Siegler, 1967, 1981), it seems unlikely to us that the congruency effect we found in our paradigm was solely influenced by the magnitude of weight for two reasons: First, the research of Siegler also demonstrated that children aged 3 years or under (as in the present study) rarely use rules (such as the rule to first use weight as judgement criterion) systematically when solving balance scale problems. Second, we did not observe effects of object identity on the production of response force, suggesting that pure differences in conceptual knowledge about weight, independent of other perceptual magnitudes (as the amount and size of the objects was the same), did not influence the response, despite the task's possible link to real-world sensorimotor experiences with lifting objects. Future research needs to show whether the here observed effects generalise to more abstract tasks with less ecological validity. Furthermore, isolating numerosity from other perceptual magnitudes, such as physical size, in a study with toddlers that involves only a limited number of trials is difficult (some authors even argue that it is impossible; Leibovich, Katzin, Harel, & Henik, 2017). Other developmental studies have tried to solve this problem and have kept the overall size constant by either manipulating the space between the objects (e.g. Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013) or the size of the single objects (e.g. Cantlon, Brannon, Carter, & Pelphrey, 2006). This, however, does not provide a solution for the problem that numerosity manipulations across few trials always covary with other perceptual properties, since varying spacing or object size introduces two other visual magnitude features that systematically depend on numerosity, namely density and (again) size. Importantly, however, studies with animals (Nieder & Miller, 2004) and adults (Izard & Dehaene, 2008) that controlled for these confounding perceptual features across a vast amount of measurement points have shown that numerosity information is extracted and processed spontaneously from numerosity displays similar to the ones used in the current study. Unfortunately, it was not feasible to fully control for these factors within a single experiment with toddlers. In the present paradigm, we thus focused on the most natural configuration in which single object size and object density are kept constant. While our results might be interpreted in line of the idea of a shared representation of numerical and motor magnitudes, we think that future research on the magnitude congruency effect, using different types of visual displays, will have to provide further insights into the underlying mechanisms of the specific effect of numerosity information on motor execution in early childhood. Importantly, however, the fact that several perceptual magnitudes (or most likely a combination of them) contribute to the observed effect does not weaken the main finding of the current study, namely an interaction between perceptual magnitude and task-irrelevant response force.

One potential concern about the main finding is that the effect of amount of objects might be driven by those children who participated in the test of force control before the experimental task and hence had previous exposure to the force button. However, there are several arguments against such an interpretation. First, the main finding of the current study is that in the experimental task children automatically coupled the perceptual magnitude (amount of objects) with the motor magnitude (response force), even though this was neither required for the task, nor beneficial. While children who first participated in the test of force control might have associated forceful responses with a single moving object on the screen, they did not ever experience a systematic coupling between perceptual and motor magnitudes in this test (i.e. perceptual magnitude was neither part of that task nor was it experimentally manipulated; in fact, it was the same single object in every trial), which might explain the later association of these magnitudes during the experimental task. Second, there was no interaction or even a trend to an interaction between the amount of objects and task order and hence no indication for any differences in the effect of perceptual amount on the production of motor force between children who first participated in the test of force control and those who first participated in the experimental task. The high statistical power of the current experiment to detect a medium sized interaction effect ensures that the absence of this interaction was not merely the result of a too low sample size. Third, despite the missing interaction, individual analyses were performed for the subgroups of children who performed the test of force control first, and those who performed the experimental task first. While both individual analyses did not reach significance on their own (most likely due to the reduced sample size after splitting the data), the descriptive pattern is opposite to the nature of the concern. That is, the group of children that did the experimental task first show a descriptively larger effect than those who did the test of force control first. Given the non-significant interaction effect, however, these post-hoc results need to be interpreted with caution. Taken together, our data provides no evidence that the magnitude congruency effect in the current study is mainly driven by those children who participated in the test of force control before the experimental task and had previous exposure to the force button.

The current finding has not only implications for our understanding of magnitude processing in perception and action but might, in addition, affects an ongoing debate about the developmental underpinnings of embodied representations of number meaning. While we cannot directly attribute the perceptual magnitude that was processed in our study to be exclusively numerosity, our data does provide evidence for an early developed generalised domain-independent representation of magnitude (Walsh, 2003) and its impact on the coupling between action and perception. As suggested by embodied theories of number representation, information about numerical size is represented within a magnitude system that evolved phylogenetically to process and represent magnitude information for the control of perception and action (cf. Walsh, 2003; Dehaene & Cohen, 2007; Lindemann et al., 2009). Importantly, the early developing automatic magnitude coupling in motor control, as observed in the current study, is in line with the notion that experiences with sensorimotor magnitudes provide the grounding for later developing representations of abstract number concepts (Fischer, Moeller, Bientzle, Cress, & Nuerk, 2011).

In conclusion, the current study shows that the processing of magnitude and its role in the coupling between perception and action can be investigated in toddlers by examining force production in a game-like experimental setting. We demonstrate an influence of the perceived amount of objects on the intensity of motor responses in 2.5- to 3-year-olds. This finding suggests, in line with the idea of a sensorimotor grounding of magnitude concepts, that an automatic coupling between perceptual and motor magnitudes emerges already in early childhood.

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