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RESEARCH ARTICLE

The common magnitude code underlying numerical and size processing for action but not for perception

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Abstract The interaction between numbers and action-related process has received increasing attention in the literature of numerical cognition. In the current study, two dual-task experiments were conducted to explore the interaction among numerical, prehension, and perceptual color/size judgments. The results revealed the commonality and distinctness of the magnitude representations that are involved in these tasks. Specifically, a photograph of a graspable object with a superimposed Arabic digit was presented in each trial. Participants were required to first judge the parity of the digit with a manual response while simultaneously planning a subsequent vocal response pertaining to the depicted object. When parity and action judgments were performed close in time, the compatibility effect between the numerical magnitude of the digit and the appropriate action (pinch vs. clutch) for the object was demonstrated in both manual and vocal responses. In contrast, such compatibility effect was absent when parity judgment was coupled with color-related or perceptual size judgment. The findings of the current study support the existence of a common magnitude code underlying numerical and non-numerical dimensions for action-related purposes, as proposed by the ATOM model (Walsh in Trends Cogn Sci 7:483–488, 2003). Furthermore, based on the selective presence of the compatibility effect, we argue that the interaction among different quantity dimensions conforms to the "dorsal-action and ventral-perception" organizational principle of the human brain.

Keywords A theory of magnitude · Dual-pathway · Action affordance · Numerical cognition · Cross-task compatibility

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Introduction

The mental representations and neural substrates that underlie magnitude processing in numerical and non-numerical domains are the main focus of an increasing number of studies. Specifically, it is under intense investigations that whether the quantity information in different dimensions is subserved by common or separable mechanisms. Many behavioral and neuroimaging studies have demonstrated similar characteristics of the processing of numerical and non-numerical quantities (see Walsh 2003, for a review). For instance, some typical properties of numerical processing, such as the distance effect (it is more time-consuming to compare two numbers when the numerical distance between them is small than large) and the size effect (it takes more time to process a digit when its numerical size is large than small), have been reported in other non-numerical magnitude dimensions. The distance effect was found when participants compared font size (Cohen Kadosh et al. 2005; Pinel et al. 2004), time duration (Dormal et al. 2006), and pitch height (Rusconi et al. 2006).

The size effect was also observed in the comparisons of line length and angle amplitude (Fias et al. 2003). In line with the proposal of a shared magnitude code underlying different quantity dimensions, numerical and non-numerical quantities have also been demonstrated to interact with each other. In the numerical Stroop paradigm, participants take more time to judge either numerical size or font size when the number magnitude and the physical size of a digit are incongruent (Cohen Kadosh et al. 2007; Schwarz and Ischebeck 2003). Such mutual interference suggests that a common magnitude code (i.e., the general mental representation of quantity) is involved in the processing of both numerical magnitude and physical size; hence the incompatible magnitude of one task-irrelevant dimension would interfere with the judgment on the other magnitude dimension.

In addition to the psychophysical evidence mentioned above, recent neuroimaging studies show that the processing of different quantity dimensions involves very similar, if not identical, brain regions. It is well-documented that the intraparietal sulcus (IPS) plays a crucial role in processing numerical magnitude (see Brannon 2006, for a review). The activation of this area is also associated with the processing of non-numerical magnitudes. For instance, comparing font size and luminance activated largely overlapping areas in the inferior parietal cortex, particularly along the IPS (Pinel et al. 2004; Cohen Kadosh et al. 2005). Similarly, Fias et al. (2003) found common activation of the left posterior IPS associated with making comparisons of lines, angles, and numbers.

Based on the converging evidence for a common magnitude code underlying different types of quantities, Walsh (2003) proposed the influential ATOM (a theory of magnitude) model. According to the ATOM model, the processing of space, time, and quantity involves a shared magnitude representation, whose neural substrates locate at the inferior parietal cortex. Walsh made several strong predictions following the notion of a shared magnitude code. For example, he suggested that "*…experiments in which responses are made to two or more magnitudes on successive trials should show cross-domain, within magnitude priming…*" (Walsh 2003, p. 487). He also pointed out that "*…the main function of the inferior parietal cortex is to encode information about the magnitudes in external world that are used in action…*" (Walsh 2003, p. 486).

Although Walsh (2003) did not make explicit predictions that the processing of magnitude information for perception and for action is dissociable, a recent report provides empirical support for such dissociation. Cavina-Pratesi et al. (2007) demonstrated that the brain areas mediating size computation for object grasping were distinct from those mediating size computation for visual perception. Specifically, the anterior intraparietal area (AIP) in the dorsal stream was more activated when participants estimated the object size for planning a grasp than simply reached to the object, while no difference in activity was observed between perceptual size judgment and pattern discrimination on the same object. Conversely, the lateral occipital (LO) cortex in the ventral stream was more activated when computing the object's perceptual size than discriminating the pattern printed on the object, while no difference was found between grasping and reaching. In addition to supporting the dual-stream model of visual processing (Milner and Goodale 1995), these results also implicate that distinct neural substrates in the ventral and dorsal streams mediate the coding of perception- and action-relevant size, respectively.

Different lines of research have consistently suggested that numerical magnitude has a close connection with the magnitude code specific for object grasping. The well-documented neural substrate of numerical representation, the IPS, was also reported to be crucially involved in the motor control of grasping movement (Culham et al. 2003), and in the retrieval of conceptual knowledge of the prehensile gesture or the size of graspable objects (Kellenbach et al. 2003; Oliver and Thompson-Schill 2003). The grasping-related intraparietal activity was even driven by tasks in which only covert naming of tools (Valyear et al. 2007) or judging action by giving vocal responses (Canessa et al. 2007) was required while no overt manual action was performed. Moreover, Andres et al. (2004) observed a congruency effect between numerical magnitude and grip aperture. When participants had to indicate the parity of a number by performing grip closure or grip opening, the electromyographic recordings showed that grip closure was initiated faster in response to small than large numbers, whereas grip opening was initiated faster to large than small numbers. Lindemann et al. (2007) also reported the numerical impact on the programming of precision and power grips. When participants performed precision or power grips to indicate the parity of a number, precision grips were initiated faster in response to small than large digits, whereas power grips were initiated faster to large than small digits. In addition, analyses of the grasping kinematics revealed that, in the reaching period, grip aperture was larger in the context of responding to large numbers than to small numbers (see also Andres et al. 2008). These findings indicate that numbers and object size exert a similar influence on the motor programming of grasping behaviors, possibly due to the common representation supporting the size estimation for actions.

The influence of numerical quantity on prehension has been reported even when the grasping action is only planned but not actually performed. Badets et al. (2007) presented rods of different lengths on the screen and asked participants to orally judge if they could grasp the rod with their thumb and index finger. Participants' judgment of graspability was found to be modulated by a task-irrelevant number presented prior to the rod: The rod's graspability tended to be overestimated following the presentation of a small number, while it was underestimated following a large number. When the rod's length was judged for a perceptual purpose without the involvement of motor imagery, however, numerical quantity had no impact on the perceptual size judgment. Such results indicated that number magnitude influenced the perceived rod length only when a potential action was involved. Badets et al. further suggested that the selective presence of the numerical effect on action judgment was due to the extent of overlap in neural substrates: Numbers and motor imagery both rely on the dorsal stream but scarcely recruit the ventral resources, while perceptual size is mainly processed in the ventral but not the dorsal stream.

To provide further evidence for the common magnitude code underlying numerical and non-numerical dimensions, and, more importantly, to test whether the interplay among different quantities could be properly delineated by the "dorsal-action and ventral-perception" organizational principle, two dual-task experiments were conducted and reported in the current study. The dual-task paradigm has been extensively employed to investigate common representations and interactive processes between dimensions (Koch and Rumiati 2006; Koch and Prinz 2005; Wenke and Frensch 2005). Particularly, the cross-task compatibility effect, a phenomenon frequently observed in dual-task experiments, is an index of the extent of "code overlap" between the processing of the two involved domains. That is, performance in both tasks would be facilitated when the representations involved in the two tasks are common and compatible with each other. In Experiment 1, a numerical task (parity judgment) was coupled with either action judgment or color-related judgment. Previous studies have demonstrated that identical stimuli could be processed preferentially in either the ventral or the dorsal stream, depending on the cognitive operations demanded by the task (Fias et al. 2002). Thus, we expect the "cross-task and within-magnitude" compatibility effect to occur between the parity and action judgments due to the parietally mediated magnitude code shared by the two tasks. On the other hand, no compatibility between the numerical task and the color-related task was expected, because color perception is underpinned by the ventral stream and no quantity computation was involved in the color task.

Although previous behavioral and neuroimaging studies have consistently suggested that numerical representation has a closer relationship with the magnitude code for object grasping than that for perceptual size estimation (Cavina-Pratesi et al. 2007; Badets et al. 2007), such a "dorsal-action and ventral-perception" distinction between the magnitude codes was hard to be reconciled with the size congruity effect in the numerical Stroop experiments. Because the font size of a digit is substantially a perceptual feature, the observation of the number-size congruity effect implies that a domain-general magnitude representation may become activated in both numerical and perceptual size processing. To directly examine the interaction among numerical magnitude, object size for grasping, and perceptual size of an object in one experiment, we carried out Experiment 2 in which the numerical task (parity judgment) was paired with either action judgment or perceptual size judgment. If the magnitude code supporting different domains is shared for action and perception, the compatibility effect should be observed no matter whether the parity judgment is paired with action or perceptual size judgment. However, if the magnitude code involved in numerical processing and action planning is distinct from that for perceptual size estimation, only the compatibility effect between parity and action judgment is expected, while it should not be observed between parity and perceptual size judgment.

Previous studies have demonstrated the compatibility effect between numerical and action processing (e.g., Andres et al. 2004; Badets et al. 2007). However, all the reports concentrated only on the numerical impact on action-related processes but not on the reverse effect. If the numerical effect on action-related tasks was truly mediated by a common magnitude code shared between the two domains, it is possible to observe the impact of action-related processing on a numerical task. To the best of our knowledge, the two experiments in the current study are the first attempt to demonstrate the mutual influence between numerical and action processing.

Experiment 1

In Experiment 1, a numerical task (i.e., parity judgment) was coupled with action- or color-related judgment in the dual-task paradigm. Participants were required to judge the parity of a digit superimposed on a graspable object and simultaneously prepare a subsequent vocal response pertaining to either the proper grasping posture or the naturalness of the object color. It should be noted that, in order to judge the proper action and the natural color of an object, the identity of the object has to be recognized in both conditions. If the magnitude code embedded in numbers is also recruited for representing object size for prehension, an effective code overlap should be revealed between the numerical and action judgment. That is, we expect to observe the compatibility effect in the performance of both parity and action judgment. On the other hand, when the numerical task was paired with color judgment, no interaction should be observed due to the lack of code overlap.

Method

Participants

Twenty-four undergraduates of National Central University in Jhongli City, Taiwan, were paid to participate in Experiment 1. They were right-handed and had normal or corrected-to-normal vision. All were naïve to the purpose of the study.

Stimuli

The stimulus set included colored digital photographs (1024 × 768 pixels) of a strawberry and a guava that could be appropriately grasped by a precision grip and a power grip, respectively. The on-screen sizes of the target objects were comparable regardless of their actual sizes in real life (guava: 7.3° in width and 8.5° in height; strawberry: 5.6° in width and 7.5° in height). In half of the photos, the strawberry and the guava were colored red, while they were colored green in the other half of the photos. In every photo, a black Arabic digit (1, 2, 8, or 9; 0.8° in width and 1.0° in height) was superimposed on the center of the fruit. The orthogonal combination of the two objects (strawberry and guava), the two colors of the object (red and green), and the four superimposed numbers (1, 2, 8, and 9) resulted in 16 stimuli in total. These 16 trials were presented in a randomized sequence in a block. There were 16 blocks that included totally 256 trials in the experiment.

Procedure and design

In every trial of the current dual-task study, the first task was always the numerical task, in which participants made a manual response to indicate the parity of the superimposed number on the object image. In half of the blocks, the second task was an action judgment, in which participants made an oral response to indicate the appropriate prehensile gesture for the object. Specifically, the correct vocal responses to the strawberry and the guava should be "*nie*" (i.e., "*pinch*" in Mandarin) and "*zhua*" (i.e., "*clutch*" in Mandarin), respectively. In the other half of the blocks, the second task was a semantic color judgment, in which participants judged if the object's image was presented in its natural color. Specifically, a red strawberry and a green guava were in their natural colors, so the correct vocal response to these objects should be "*shi*" (i.e., "*yes*" in Mandarin). A green strawberry and a red guava were not in their natural colors, so the correct vocal response to these objects should be "*fou*" (i.e., "*no*" in Mandarin). These two types of trials were grouped in two separate experimental sessions. The order of the two sessions was counterbalanced across participants.

In the action condition (i.e., when the parity judgment and action judgment were performed close in time), the participants were explicitly encouraged to imagine the proper handgrip posture for the object, and the relationship between the object size in real life and the appropriate grasping posture was emphasized. In contrast, when the parity judgment was coupled with the color judgment, the participants were told to concentrate on the image color of the object while ignoring its associated action.

In each trial, a central fixation was presented for 700 ms, followed by the image of an object with a number superimposed on it. Participants were instructed to make parity judgment to the number by pressing one of the two buttons on the response box via their index and middle fingers, and then utter their vocal responses regarding either the appropriate grasping postures or the naturalness of the object's color. They were required to perform the two responses in the strict serial order. The mapping between odd/even responses and the fingers used to indicate the parity was counterbalanced across participants. The stimulus appeared on the screen until the parity judgment was made or the time limit of 1-s was reached. Immediately after the keypress response, the stimulus object disappeared and was replaced by a row of six @ signs. Because the object could no longer be seen as soon as the manual response was made, participants had to judge the parity of the digit and prepare the subsequent vocal response at the same time. The @ sign stayed on the screen until a vocal response was detected by the microphone or a time limit of 2.5 s was reached. When the vocal response was registered, the computer screen turned blank until the experimenter recorded the accuracy of the vocal response and triggered the next trial. Only correct vocal responses after a manual response were accepted. The reaction time (RT) of the manual response was defined as the time interval between the stimulus onset and the keypress. The vocal RT was defined as the time interval between the onsets of the manual and vocal responses.[1]

Participants sat in front of a computer screen with a viewing distance of approximately 60 cm. They were asked to position the index and middle fingers of their right hand onto two horizontally aligned buttons on a response box. The two buttons were 3.3 cm apart. A desk microphone

[1] In fact, when we defined the vocal RT as the interval between the stimulus onset and the vocal response, we obtained similar results to those reported in the present study. However, when the vocal RTs were computed from the stimulus onset, they would inevitably include the duration of the manual RTs. As a result, even if we observed the compatibility effect in the vocal responses, it is not clear whether the effect is contaminated by the compatibility effect in the manual responses. In order to evaluate the compatibility effect in the vocal and manual responses independently, we chose to report the vocal RTs that were measured from the onset of manual responses.

was positioned in front of the participant to register vocal responses. Before the experimental sessions, participants previewed each photo of the stimuli to be familiar with the fruits in their natural and unnatural colors. All participants were able to recognize the fruit correctly based on the contour, texture, and shape of the stimulus, despite the change of the fruit's skin color. Two practice blocks (32 trials in total) were administered to each participant before the experimental blocks to ensure their familiarity with the trial procedure.

Results

Trials with at least an error in the manual and vocal responses or with an order error of these two types of responses were discarded, which resulted in the deletion of 10.8% of the total data. Trials whose RT was outside of two standard deviations or faster than 100 ms (manual: 1.5%; vocal: 2.0%) were also excluded from further analyses. The remaining manual and vocal RTs were submitted to separate analyses of variance (ANOVAs) that were both with three within-participant factors of second task (action judgment vs. semantic color judgment), number magnitude (1 and 2 vs. 8 and 9), and object type (strawberry vs. guava).[2]

Keypress responses of parity judgment

The main effect of number magnitude was significant, $F(1, 23) = 18.5$, MSE = 1362, $P < 0.001$. Responding to small numbers (565 ms) was faster than responding to large numbers (588 ms). The number by object interaction was also marginally significant, $F(1, 23) = 3.2$, MSE = 402, $P = 0.08$. All other main effects and all two-way interactions were not significant (all Ps > 0.14). Critical to our research purpose, the interaction among second task, number magnitude, and object type achieved significance, $F(1, 23) = 6.2$, MSE = 816, $P < 0.03$ (see Fig. 1). Further analyses showed that the interaction between number magnitude and object type was only present when the parity judgment was performed immediately before the action judgment, $F(1, 23) = 13.7$, MSE = 419, $P < 0.01$, but was absent when the parity judgment was followed by the semantic judgment of color, $F < 1$. Pair-wise comparisons revealed that responding to a large number was faster when participants simultaneously prepared to say "clutch" to a guava (579 ms) than to say "pinch" to a strawberry (600 ms), $t(23) = -2.23$, $P < 0.04$. Conversely, responding to a small number was faster when they prepared to say "pinch" to a strawberry (562 ms) than to say "clutch" to a guava (573 ms), $t(23) = -1.6$, $P = 0.11$, albeit this difference did not reach significance.

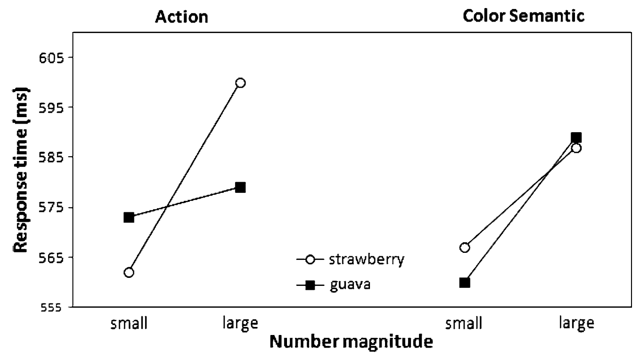

Fig. 1 Mean reaction times of the manual responses of the parity judgment in Experiment 1 as a function of second task (action judgment/semantic color judgment), number magnitude (small/large), and object type (strawberry/guava)

Vocal responses of action and semantic color judgment

The main effect of object type was marginally significant, $F(1, 23) = 3.7$, MSE = 1469, $P = 0.06$. No other main effects or any two-way interaction reached significance (all Ps > 0.16). Most importantly, the ANOVA revealed a significant three-way interaction among second task, number magnitude, and object type, $F(1, 23) = 7.9$, MSE = 531, $P < 0.02$ (see Fig. 2). Further analyses indicated that the interaction of number magnitude and object type was only observed in the condition of action judgment, $F(1, 23) = 16.3$, MSE = 351, $P < 0.01$, but not in the condition of semantic color judgment, $F < 1$. Pair-wise comparisons showed that saying "pinch" to a strawberry was faster when being preceded by responding to a small number than to a large number (516 vs. 531 ms), $t(23) = -2.6$, $P < 0.02$. Conversely, saying "clutch" to a guava was faster when being preceded by reacting to a large number than to a small number (507 vs. 523 ms), $t(23) = -2.7$, $P < 0.02$.

Discussion

The findings from Experiment 1 demonstrated the "cross-domain and within-magnitude" priming effect between

[2] A within-participant ANOVA on error rates, similar to the one conduced on RT data, revealed no significant main effects or interactions, all Ps > 0.16. To examine whether there was a SNARC effect, we also submitted the RT data into a mixed-design ANOVA with finger (index vs. middle) and number (small vs. large) as two within-participant factors, and rule (odd-index/even-middle vs. odd-middle/even-index) as a between-participant factor. The results only revealed the main effects of finger, $F(1, 22) = 10.0$, $P < 0.01$, and number, $F(1, 22) = 18.4$, $P < 0.001$, while the finger × number interaction (i.e., the SNARC effect) was not significant, $F(1, 22) = 1.3$, $P > 0.26$. The lack of the SNARC effect might be due to the close distance, hence small spatial displacement, between the two buttons for manual responses.

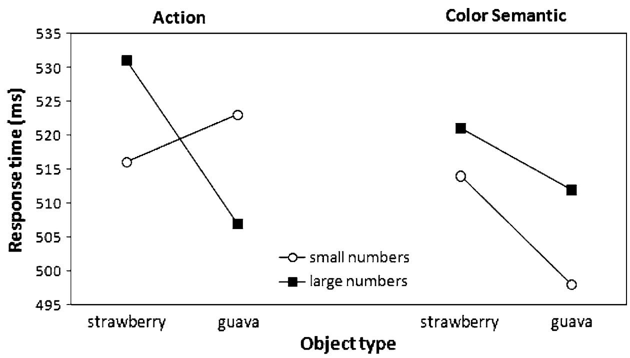

Fig. 2 Mean reaction times of the vocal responses of the action judgment and semantic judgment in Experiment 1 as a function of second task (action judgment/semantic color judgment), number magnitude (small/large), and object type (strawberry/guava)

numerical and action processing. That is, when parity judgment and action judgment were performed in close temporal succession, the performance in both tasks was facilitated when the magnitude code embedded in numerical and action-related processes was compatible. In sharp contrast, when parity judgment and color-related judgment were successively performed on exactly the same set of stimuli, there was no interaction between number magnitude and object size. In addition to demonstrating the mutual influence between numerical and action representations via the common magnitude code, these results also showed that the magnitude code of object size did not automatically interact with numbers when no action was involved in the task.

Although the division of labor between the dorsal and ventral streams provides an adequate theoretical framework for the selective presence of the cross-task compatibility among numerical and action-related processing, other mechanisms might be able to account for the current findings as well. According to the polarity correspondence principle (Proctor and Cho 2006), small digits and the gesture of "pinch" might both correspond to negative polarity, while large digits and the gesture of "clutch" might both correspond to positive polarity; thus, a polarity mapping might exist between the two tasks. In contrast, the color-related responses did not meaningfully correspond to numbers or any other dimensions. Such lack of conceptual association between colors and polarity might explain the absence of the cross-task compatibility effect. In Experiment 2, we addressed this issue by exploring whether numerical magnitude would interact with any other quantity information with the potential to generate a meaningful polarity correspondence to numbers, or, alternatively, numerical magnitude would only interact with the quantity information associated with action.

Experiment 2

In Experiment 2, we intended to clarify whether a domain-general magnitude code is involved in both action- and perception-related processes, or different magnitude representations are selectively involved according to the "ventral-perception and dorsal-action" organizational principle. Also, in Experiment 1, the real-life size of the depicted objects and their image size were not completely independent. That is, the objects appropriate for power grip still appeared slightly larger than those appropriate for precision grip. Thus, the interaction between number magnitude and object type could possibly (despite unlikely) stem from the compatibility between numbers and the perceptual size of the object. To address these issues directly, in Experiment 2 we systematically manipulated the image size of each object and required participants to process the image size in the perceptual condition. Because the concept of quantity associated with an object had to be accessed in both action and perpetual conditions, and also because polarity mapping between numbers and other quantities could exist in both conditions, we were able to independently evaluate the interaction between numerical magnitude and action representation, as well as the interaction between numerical magnitude and image size.

Method

Participants

Twenty-four undergraduates of National Central University in Jhongli City, Taiwan, were paid to participate in Experiment 2. All participants were right-handed and had normal or corrected-to-normal vision. None of them had participated in Experiment 1.

Stimuli

The photos of strawberries and guavas were again used as the stimuli. All fruits were presented in their natural color (i.e., red strawberries and green guavas). However, the image size of the fruit was manipulated. The fruit was either presented in its normal size (small strawberry: 3.3° in width and 4.3° in height; large guava: 8.7° in width and 10.5° in height) or in an unnatural size (large strawberry: 8.0° in width and 10.5° in height; small guava: 3.5° in width and 4.0° in height). In other words, when the fruit was presented in an unnatural size, the fruit affording a precision grip (i.e., strawberry) was enlarged to become as large as a guava, whereas the fruit affording a power grip (i.e., guava) was shrunk to become as small as a strawberry. As in the previous experiment, a black Arabic digit (1, 2, 8, or 9) was superimposed on the centre of each photo. The orthogonal combination of the two fruits (strawberry and guava), the two sizes of the fruits (small and large), and the four superimposed numbers (1, 2, 8, and 9) resulted in 16 stimuli in total.

Procedure and design

The trial procedure and the design were identical to those in Experiments 1, except for the following modifications: The parity judgment was coupled with either action judgment (to decide whether the proper handgrip gesture for the target fruit was a precision grip or a power grasp) or perceptual size judgment (to judge whether the image size of the target fruit was larger than a reference rectangle or not). Before participants began the experimental session of perceptual size condition, they were clearly shown that the image size of a large guava and a large strawberry was both larger than a reference rectangle (6.0° × 7.0°), while the size of a small guava and a small strawberry was both smaller than the same rectangle. The reference rectangle was not presented in the experimental trials. Similar to Experiment 1, the correct vocal responses to the image of a guava and a strawberry were "*zhua*" and "*nie*", respectively, in the condition of action judgment. The correct vocal responses to large and small images, irrespective of the fruit type, were "*shi*" and "*fou*", respectively, in the condition of perceptual size judgment. The parity judgment was performed with action judgment or perceptual size judgment in separate sessions.

Results

After excluding the trials with at least one incorrect response or with the order error of the manual and vocal responses (10.9%) and outliers (i.e., RTs outside of 2 SDs or faster than 100 ms; 1.1% in manual responses and 2.3% in vocal responses), we analyzed the remaining RT data of manual and vocal responses separately with a repeated-measure ANOVA, with second task (action judgment vs. perceptual size judgment), number magnitude (1 and 2 vs. 8 and 9), object type (strawberry vs. guava), and image size (small vs. large) as within-participant variables.[3]

[3] A similar analysis of error rates only revealed a significant main effect of number magnitude, $F(1, 23) = 5.1$, $P < 0.05$. Responses to large numbers (11%) were more error prone than responses to small numbers (9.3%). All other main effects and interactions were not significant (all Ps > 0.11). Similar to Experiment 1, in the analysis of the SNARC effect, we only detected the main effect of number, $F(1, 22) = 31.4$, $P < 0.001$, and the interaction between finger and rule, $F(1, 22) = 14.7$, $P < 0.01$. The finger × rule interaction actually reflected a parity effect, namely, RTs to odd numbers were slower than those to even numbers in both finger-to-parity assignments (both Ps < 0.05).

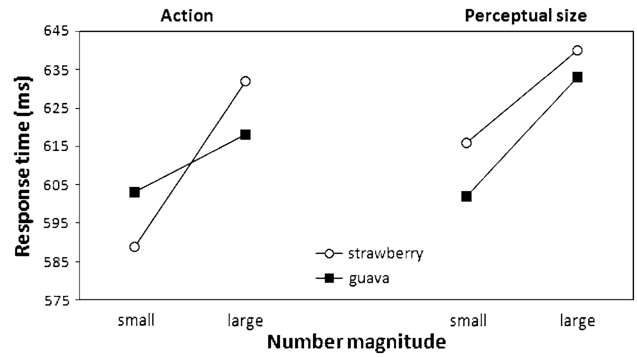

Fig. 3 Mean reaction times of the manual responses of the parity judgment in Experiment 2 as a function of second task (action judgment/perceptual size judgment), number magnitude (small/large), and object type (strawberry/guava)

Keypress responses of parity judgment

Number magnitude had a significant main effect, $F(1, 23) = 20.8$, MSE = 3678, $P < 0.001$. Small numbers (603 ms) were reacted to faster than large numbers (631 ms). Other main effects, all two-way interactions, and the four-way interaction among all variables were not significant (all Ps > 0.12).

The most critical finding from the ANOVA was the significant three-way interaction among second task, number, and object type, $F(1, 23) = 6.1$, MSE = 1185, $P < 0.03$. Further analyses revealed that the two-way interaction between number magnitude and object type was significant in the action condition, $F(1, 23) = 12.4$, MSE = 760, $P < 0.01$, but not in the perceptual size condition, $F < 1$ (see Fig. 3). Pair-wise comparisons showed that responding to a small number was faster when participants planned to say "pinch" (589 ms) than "clutch" (603 ms), $t(23) = -2.3$, $P < 0.04$, whereas responding to a large number was faster when they prepared to say "clutch" (618 ms) than "pinch" (632 ms), $t(23) = -3.1$, $P < 0.01$.

Also relevant to our interest, the three-way interaction among second task, number, and image size was also significant, $F(1, 23) = 5.5$, MSE = 865, $P < 0.03$. Further analyses revealed that the two-way interaction between number magnitude and image size was detected in the action condition, $F(1, 23) = 13.9$, MSE = 516, $P < 0.01$, but not in the perceptual size condition, $F < 1$. Pair-wise tests showed that, in the condition of action judgment, responding to a small digit was faster when the digit appeared in a small object image (586 ms) than when it appeared in a large object image (606 ms), $t(23) = -3.9$, $P < 0.01$, whereas the influence of image size was not observed for large numbers ($P > 0.28$).

Vocal responses of action and perceptual size judgment

The four-way ANOVA revealed significant main effects of object type, $F(1, 23) = 13.7$, MSE = 2562, $P < 0.001$, and image size, $F(1, 23) = 22.0$, MSE = 2945, $P < 0.001$. We also observed significant three-way interactions among second task, number, and object type, $F(1, 23) = 6.7$, MSE = 916, $P < 0.02$, and among second task, number magnitude, and image size, $F(1, 23) = 7.45$, MSE = 1204, $P < 0.02$. Moreover, the four-way interaction among all variables achieved marginal significance, $F(1, 23) = 3.2$, MSE = 1021, $P = 0.08$.

In order to disentangle the complicated interaction pattern involving all four factors, we performed separate analyses according to the two second tasks. In the three-way ANOVA of the RTs from the action judgment,[4] the three-way interaction among number magnitude, object type, and image size reached marginal significance, $F(1, 23) = 3.2$, MSE = 685, $P = 0.08$. Thus, further tests were conducted to examine how number magnitude and image size interacted for each type of objects. In the vocal responses of judging the prehensile action for a strawberry (i.e., answering "*pinch*"), the main effect of number magnitude was significant, $F(1, 23) = 7.7$, MSE = 1067, $P < 0.02$. The vocal responses of saying "pinch" were faster after responding to a small than large number (506 ms vs. 525 ms; see Fig. 4). Similarly, in the vocal responses of judging the action for a guava (i.e., answering "*clutch*"), the main effect of number magnitude was also significant, $F(1, 23) = 4.5$, MSE = 812, $P < 0.05$. Saying "clutch" to a guava was facilitated following reacting to a large than small number (465 vs. 478 ms; see Fig. 4). Besides, in the RTs of answering "*clutch*", we also observed a significant interaction between number magnitude and image size, $F(1, 23) = 8.6$, MSE = 812, $P < 0.01$. Pair-wise tests showed that saying "clutch" to a large guava was faster after responding to a large than small number (461 vs. 490 ms), $t(19) = -3.5$, $P < 0.01$. In contrast, in the same vocal responses to a small guava, there was no difference between the contexts of small number and large number ($P > 0.56$).

In sharp contrast with the findings from the action judgment, neither the three-way nor any two-way interaction was significant in the results of perceptual size judgment (all Ps > 0.17).

[4] In this analysis, we also observed a significant main effect of object type, $F(1, 23) = 41.3$, $P < 0.001$. The RTs of uttering "*nie*" (pinch; 516 ms) to a strawberry was slower than those of uttering "*zhua*" (clutch; 471 ms) to a guava (see Fig. 4). Such an effect merely indicated the difference in voice onset time, i.e., the nasal sound "*nie*" took more time to pronounce than the fricative sound "*zhua*".

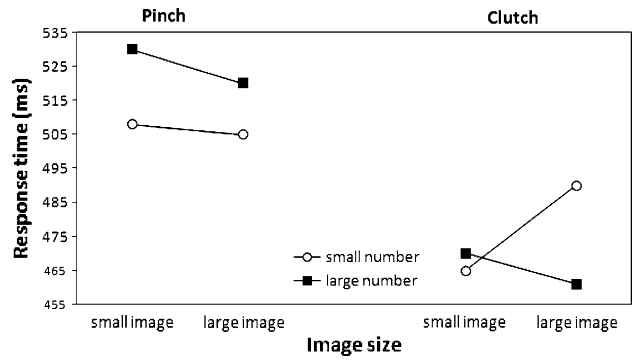

Fig. 4 Mean reaction times of the vocal responses of the action judgment in Experiment 2 as a function of object type (strawberry/guava), number magnitude (small/large), and image size (small/large)

Discussion

In Experiment 2, two main findings were obtained: First, in the condition of action judgment, we replicated the cross-task compatibility effect between number magnitude and object type in both manual and vocal responses, even when the influence of image size was separately estimated. Second, the compatibility between numbers and object type, as well as that between numbers and image size, was absent in the condition of perceptual size judgment, despite the task necessitated the concept of magnitude to be accessed. These findings highlighted the importance of action planning/imagery in eliciting the interaction between numbers and the magnitude code in other domains.

If the interactions between numbers and grasping gestures were truly caused by the polarity correspondence between dimensions (Proctor and Cho 2006), we should observe the compatibility effect between numbers and image size in the condition of perceptual size judgment, because small digits and small images both correspond to negative polarity, while large digits and large images both correspond to positive polarity. The absence of any compatibility effect in the perceptual condition clearly argues against the prediction from the polarity correspondence account. Instead, the current findings are consistent with Badets et al. (2007) in showing that the interplay between quantities generally conforms to the "dorsal-action and ventral-perception" organizational principle, as the mutual influence between numerical and prehensile processing was observed only when the quantity code involved in both tasks was dorsally mediated.

General discussion

In the present study, two dual-task experiments were conducted to explore whether the interaction among the numerical and non-numerical dimensions could be properly specified by the "dorsal-action and ventral-perception" division of the human brain. According to Walsh (2003), the inferior parietal cortex is the brain locus of a common magnitude system for action. Based on this notion and recent evidence for separable neural mechanisms computing action- and perception-relevant sizes (Cavina-Pratesi et al. 2007), we hypothesized that numbers are more likely to interact with other quantities when the second task involves the appropriate action toward an object than when the second task involves purely perceptual processing on the same object, such as its image size and color. The results of both experiments in the current study support our prediction. In Experiment 1, the compatibility between number magnitude and object size was observed when judging the parity of a digit was performed closely in time with judging the appropriate prehensile gesture for an object. However, when parity judgment was paired with semantic color judgment of the very same object, no interaction was observed. The results of Experiment 2 replicated the cross-task compatibility effect between number magnitude and object size, even when the contribution from the image size of the stimulus object was independently evaluated. Critically, the interaction involving number magnitude and other quantity dimensions was only detected when the action judgment was involved, but not when the perceptual size judgment was required.

The current results are consistent with previous studies in showing the close relationship between numerical and action processing (Andres et al. 2004; Badets et al. 2007; Lindemann et al. 2007): Numerical magnitude interacts with the action representation of the object concept (i.e., precision or power grip), as well as with the physical size of the object (i.e., small or large image), in a "cross-domain and within-magnitude" manner. Our findings, together with those of Badets et al. (2007), also argue against the existence of a generalized magnitude code for the computation of all sorts of quantities. Instead, these findings suggest that the human brain utilizes the "ventral-perception and dorsal-action" neurofunctional structure as a framework for different magnitudes to be represented and to interact with each other. Depending on one's purpose of particular behaviors, different magnitude representations residing in the ventral and dorsal pathways would be differentially recruited for solving the task at hand, and the interaction among the magnitude code would be modulated by the extent of neural overlap.

In line with the idea that the extent of neural overlap plays a crucial role in mediating the interaction between numbers and action, the same principle has been shown to adequately account for the interaction between numbers and spatial locations. In a series of experiments, Fias et al. (2001) and Lammertyn et al. (2002) demonstrated that the effect of Spatial-Numerical Association Response Codes (the SNARC effect; left-sided responses are initiated faster to small than large digits, and vice versa for right-sided responses) was only observed when participants judged the orientation of the stimulus digit, but not when they judged the color of the digit. Fias et al. (2001) argued that the amount of overlap in neural underpinnings modulated the presence of the SNARC effect. Specifically, the processing of both numbers and orientation relies on parietal areas, while color perception is mainly subserved by the inferior temporal cortex of the ventral stream (Zeki et al. 1999).

Although the ATOM model (Walsh 2003) did not specifically predict whether the interaction between magnitudes of different domains is unidirectional or reciprocal, the mutual influence between numbers and spatial representations has been reported: Perceiving task-irrelevant numerical information biased the detection of a spatially lateralized target (Fischer et al. 2003), and the presence of task-irrelevant spatial cues biased the semantic processing of target digits (Stoianov et al. 2007). In a series of dual-task experiments similar to the current study, Caessens et al. (2004) observed that the selection of a left or right manual response was influenced by a subsequent vocal response of uttering a small or large number, and the vocal response of saying a small or large number was also modulated by the foregoing manual response. Similar to the mutual influence between numbers and space, the current results demonstrate the mutual influence between numbers and action. Specifically, the compatibility effect revealed in the manual responses of the parity task suggests that the action representations related to object size could modulate numerical processing, while the compatibility effect revealed in the vocal responses of the action judgment task suggests the effect in the reversed direction. In other words, the two interactions in the manual and vocal responses together lend support to the mutual influence between numerical and action concepts, which is assumed to arise from the mediation of the common magnitude code.

Another intriguing aspect of the current results is that the mapping between number magnitude and action representations could be flexibly established or abolished, depending on the goal of participants' response(s). The flexibility of the representational overlap across tasks has been demonstrated in previous dual-task experiments (Koch and Rumiati 2006; Koch and Prinz 2005; Wenke and Frensch 2005), however, most of these studies focused on the flexibility of spatial/perceptual compatibility across tasks. In addition to replicating the adjustability of the cross-task compatibility effect, the current study further indicated that such a phenomenon could be demonstrated between two non-perceptual domains, such as the abstract concept of numerical quantity and the mental size of an object.

In the present study, the image of a graspable object and the digit were presented simultaneously. Thus, with the current trial procedure, we cannot infer which task was mentally performed first while the other task was performed second, even though the two tasks were performed in a strictly sequential manner. However, our argument for the mutuality is not based on the execution order of the two tasks. No matter one task is performed first or second, the critical factor for a cross-task interaction to occur is that the "codes" involved in two processes are common and overlap in time. Furthermore, it has been extensively documented in the literature of dual-task studies that when a mental representation is involved in both tasks, this representation would be activated before the execution of the first response, and would consequently influence both the performances in the first and second tasks (see Hommel 1998, for a detailed discussion). Taking advantage of the processing overlap in the dual-task paradigm, the current study clearly demonstrates the compatibility between numbers and other magnitudes in both manual and vocal responses, suggesting the mutual influence between numerical and action representations.

In sum, the implications of the current report are twofold: First, our results support a common magnitude code underlying different quantity dimensions for action. The interaction between numerical and non-numerical magnitudes largely conforms to the "dorsal-action and ventral-perception" organizational principle. Second, we demonstrate not only the numerical influence on an action judgment but also the reverse effect, that is, the action-related influence on numerical processing, which supports and extends the prediction of the ATOM model (Walsh 2003).

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