Common spatial organization of number and emotional expression: A mental magnitude line

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ABSTRACT

Converging behavioral and neural evidence suggests that numerical representations are mentally organized in left-to-right orientation. Here we show that this format of spatial organization extends to emotional expression. In Experiment 1, right-side responses became increasingly faster as number (represented by Arabic numerals) or happiness (depicted in facial stimuli) increased, for judgments completely unrelated to magnitude. Additional experiments suggest that magnitude (i.e., more/less relations), not valence (i.e., positive/negative), underlies left-to-right orientation of emotional expression (Experiment 2), and that this orientation accommodates to the context-relevant emotion (e.g., happier faces are more rightward when judged on happiness, but more leftward when judged on angriness; Experiment 3). These findings show that people automatically extract magnitude from a variety of stimuli, representing such information in common left-to-right format, perhaps reflecting a *mental magnitude line*. We suggest that number is but one dimension in a hyper-general representational system uniting disparate dimensions of magnitude and likely subserved by common neural mechanisms in posterior parietal cortex.

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1. Introduction

The metaphor of the *mental number line* is often invoked to illustrate the deep mental connection between space and number (for review, see Hubbard, Piazza, Pinel, & Dehaene, 2005). In a classic demonstration, known as the *SNARC* (Spatial–Numerical Association of Response Codes) effect, Dehaene, Bossini, and Giraux (1993) found that parity (odd/even) judgments were faster when Western adult participants responded to smaller numbers (e.g., 1 and 2) on the left side of space (e.g., with their left hand) and to larger numbers (e.g., 8 and 9) on the right (e.g., with their right hand). It has also been shown that people randomly generate smaller numbers when facing leftward and larger numbers when facing rightward (Loetscher, Schwarz, Schubiger, & Brugger, 2008), and that numerical processing elicits shifts in spatial attention, with smaller and larger numbers speeding detection of left- and right-side visual stimuli, respectively (Fischer, Castel, Dodd, & Pratt, 2003). These findings suggest that representations of number are fundamentally spatial in nature, with increasing values mentally organized in left-to-right orientation.

Other recent studies suggest that spatial organization extends to temporal information. Duration is underestimated for left-side

stimuli and overestimated for right-side stimuli (Vicario et al., 2008), and people are faster to respond to shorter and longer durations (Vallesi, Binns, & Shallice, 2008), as well as to judge earlier and later onset timing (Ishihara, Keller, Rossetti, & Prinz, 2008), with their left and right hands, respectively. Together, these findings suggest that left-to-right orientation is a property of both numerical and temporal representation: "less" time is represented on the left side of space and "more" time on the right, like smaller and larger numbers, respectively.

Evidence of common neural mechanisms in posterior parietal cortex, particularly the intraparietal sulcus (IPS), for number (Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007; Piazza, Pinel, Le Bihan, & Dehaene, 2007), duration (Leon & Shadlen, 2003; Maquet et al., 1996), and spatial extent (Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Sereno, Pitzalis, & Martinez, 2001) is suggestive of a system of generalized magnitude representation (Walsh, 2003; see also Gallistel & Gelman, 2000; Lourenco & Longo, 2010), in which such dimensions share not only cerebral territory but also representational structure, including left-to-right orientation (for reviews, see Bueti & Walsh, 2009; Cantlon, Platt, & Brannon, 2009; Cohen Kadosh, Lammertyn, & Izard, 2008). Indeed, damage to right posterior parietal cortex, or more distributed parieto-frontal circuits, can produce representational deficits that extend across magnitude dimensions (Bisiach & Vallar, 2000). Patients with hemispatial neglect, for example, show significant rightward bias (i.e., ignoring the left side of space) not only when

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bisecting physical lines, but also when estimating the midpoint of numerical intervals (i.e., overestimating relative to the actual mid-point, consistent with a "rightward" bias on a left-to-right mental number line) (Zorzi, Priftis, & Umiltà, 2002; for evidence with healthy participants, see Longo & Lourenco, 2007, 2010; Lourenco & Longo, 2009). Similar findings when neglect patients judge temporal order for lateralized stimuli (Snyder & Chatterjee, 2004) suggest that impaired processing along the left–right spatial axis alters the mental organization of both number and time.

In the present research, we examine the extent to which such organization generalizes to less prototypical sources of magnitude information. Because of their clearly delineated more versus less relations, number and duration might be considered prototypical *prothetic* dimensions – that is, dimensions characterized by quantity, or "how much," often contrasted with *metathetic* dimensions such as pitch and hue, characterized by quality, or "what kind" (Stevens, 1957, 1975). However, countless other experiences can also be described in more/less terms, though perhaps not primarily. For example, the concept of happiness may be characterized, at least in part, in terms of degree – that is, how happy one is at a given moment. Might a system of generalized magnitude representation be so abstract as to encompass even socio-emotional cues such as facial expressions exhibiting happiness? If so, the representation of happiness, among other emotions, might also be expected to show the property of left-to-right orientation.

We use emotional expression as the test case of generalization because there are clear reasons why such a domain might be excluded from a general magnitude system, and hence not mentally organized in any consistent spatial orientation. Unlike for number, other features (e.g., valence) may be equally, if not more, salient than degree of emotion (e.g., Bradley & Vrana, 1993; Nakashima et al., 2008), and representations of emotion have often been regarded as categorical, rather than graded, in nature (e.g., Ekman, 1992). Moreover, while cultural tools such as rulers reinforce left-to-right orientation for number, emotional expression has no obvious spatial instantiation in the physical world. Happier people, for example, do not tend to congregate on the right side of space. Given the substantive differences between number and emotional expression, a common pattern of spatial organization would provide compelling support for a hyper-general system of magnitude representation, encompassing dimensions both prototypical and otherwise.

2. Experiment 1

This experiment examined whether happiness, as indexed by facial expression, is mentally organized in left-to-right orientation, like number. Participants completed both Number and Face tasks in which response choices were paired with left- and right-side response keys. The Number task used the canonical SNARC paradigm (e.g., Dehaene et al., 1993, Experiment 1), with participants making parity (odd/even) judgments to numbers 0–9. Because parity judgments are irrelevant to magnitude (i.e., a larger number is no more likely to be odd or even than a smaller number), reliable left-to-right orientation in this paradigm suggests that spatial organization is relatively automatic (Fias & Fischer, 2005). Indeed, left-to-right orientation of number has been observed using other types of magnitude-irrelevant judgments as well (e.g., Fias, Lauwereyns, & Lammertyn, 2001). The Face task was designed to mirror the Number task in this respect. Participants were presented with images of human faces whose expressions varied in happiness, and were asked to judge the gender (male/female) of each face. Thus, judgments in both tasks involved no explicit consideration of magnitude, whether numerical or emotional.

2.1. Method

2.1.1. Participants

Eighteen Emory University undergraduates (12 female) participated for course credit. As measured by the Edinburgh Handedness Inventory (EHI; Oldfield, 1971), the majority of participants (14) were right-handed ($M = 49$; range: −53 to 100). All had normal or corrected-to-normal vision and gave written consent to participate. Procedures were approved by the local ethics committee.

2.1.2. Stimuli

Number stimuli were Arabic numerals (0–9), presented centrally on a computer screen in black font on a white background (Arial font, 25×15 mm, $2.9° \times 1.7°$). Face stimuli (90×65 mm, $10.3° \times 7.4°$), also presented centrally on a white background, were from the NimStim Face Stimulus Set (Tottenham et al., 2009). Images of six models (three female), each exhibiting four distinct expressions (which we labeled *neutral*, *happy*, *very happy*, and *extremely happy*; see Fig. 1a), were selected based on validity ratings, for a total of 24 grayscale images.

2.1.3. Procedure

Each participant completed both Number and Face tasks (order counterbalanced). In the Number task, participants made parity judgments on each trial by pressing left ("Q") and right ("P") computer keys. Participants completed two blocks of trials: one in which even responses were assigned to the left key and odd responses to the right key, and the other with the reverse assignment (order counterbalanced). Each block consisted of 10 practice trials and 90 test trials (each number presented nine times; random order). In the Face task, participants made gender judgments on each trial by pressing the same left and right keys. As in the Number task, participants completed two blocks of trials: one in which male responses were assigned to the left key and female responses to the right key, and the other with the reverse assignment (order counterbalanced). Each block consisted of 12 practice trials and 96 test trials (24 face stimuli presented four times each, with 24 trials of each expression; random order). Each trial began with a fixation cross presented centrally for 500 ms. The target stimulus (number or face) followed, remaining onscreen until participants made a response. The intertrial interval was 500 ms. Instructions emphasized both speed and accuracy.
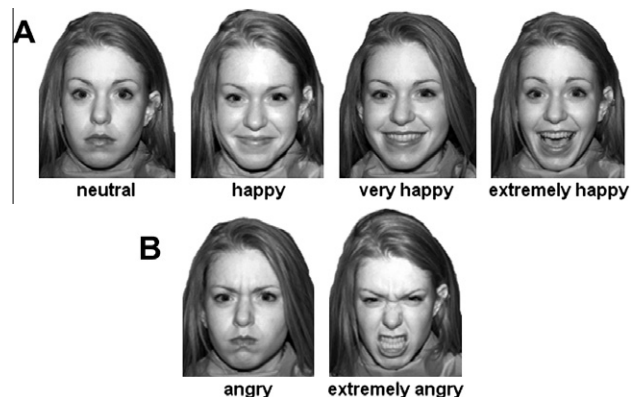

Fig. 1. (A) Range of facial expressions used in Experiment 1. (B) Angry facial expressions used in Experiments 2 and 3; these experiments also included *neutral* (Experiment 2 only), *happy*, and *extremely happy* expressions. All face stimuli were selected from Tottenham et al. (2009).

2.2. Results

2.2.1. Ratings of face stimuli

To approximate the psychological distance between each of the facial expressions in the Face task, we obtained ratings of emotional magnitude (EM). A separate group of participants (N = 10) assigned ratings from 1 to 7 (1 = "neutral expression", 7 = "very emotional expression") to each of the 24 face stimuli (presented in random order). Mean ratings for the four expressions were 1.57 (neutral), 3.35 (happy), 4.67 (very happy), and 5.98 (extremely happy). In analyses of the rating data by participant and by item (i.e., face model), all pairwise comparisons among the four expressions were significant (all $ps < .005$), indicating that expressions differed in EM in the following order of increasing magnitude: neutral < happy < very happy < extremely happy.

2.2.2. Slope analyses

For the Number and Face tasks, trials in which participants responded incorrectly (Number task: 5.0% of trials; Face task: 2.3%), or in which reaction times (RTs) were greater than 2.5 SD from individual means (Number task: 2.7%; Face task: 2.8%), were

excluded. Overall mean RTs on remaining trials were 596 ms (SD = 119) and 546 ms (SD = 77) in Number and Face tasks, respectively. Mean RTs for each participant were computed for left and right responses separately for each digit pair (0–1, 2–3, 4–5, 6–7, and 8–9) in the Number task (following previous research; e.g., Dehaene et al., 1993), and for each facial expression (neutral, happy, very happy, extremely happy) in the Face task. Left responses were subtracted from right responses for a measure of RT differences (dRT) for each digit pair and facial expression.

For the Number task, dRT values were regressed on digit magnitude to produce the unstandardized slope coefficient of the best-fitting linear regression. If, as shown in previous research, smaller and larger numbers elicit relatively faster left and right responses, respectively, this regression-based analysis of the SNARC effect (see Fias & Fischer, 2005) should yield a negative slope. For the Face task, dRT values were regressed on mean EM ratings for each expression. If happiness is mentally organized in left-to-right orientation, right responses should become relatively faster with increasing happiness, also yielding a negative slope.

The average slope coefficients differed significantly from zero on both Number (M = −6.26 ms/digit, SD = 10.18; see Fig. 2a), $t(17) = 2.61$, $p = .02$, $d = .62$, and Face tasks (M = −6.20 ms/EM, SD = 10.42; see Fig. 2b), $t(17) = 2.52$, $p = .02$, $d = .59$, reflecting reliable left-to-right orientation of number and happiness.[1] There was a positive, albeit non-significant, correlation between slopes on the two tasks ($r = .25$, $p = .32$; see Sections 3.2.2 and 5.1 for further discussion). A 2 (task: Number or Face; within-subjects) × 2 (order of tasks; between-subjects) analysis of variance (ANOVA) on the slope data yielded no significant main effects of task or order, and no significant interaction ($ps > .3$), suggesting that the strength of spatial organization was comparable across the two tasks.[2]

2.3. Discussion

The results of Experiment 1 suggest that, rather than being unique to number (or other prototypical magnitude cues such as duration), left-to-right orientation extends to socio-emotional stimuli, for which more/less relations are only one of many defining features. Particularly striking is that spatial organization was observed for happiness even though emotional expression was irrelevant to the task. As with parity judgments of number, gender judgments of faces do not co-vary with magnitude; male faces are no more likely than female faces to depict happier expressions. Moreover, while previous studies have suggested that gender judgments of faces are relatively unaffected by categories of emotion (e.g., judging gender for a uniform set of happy expressions is just
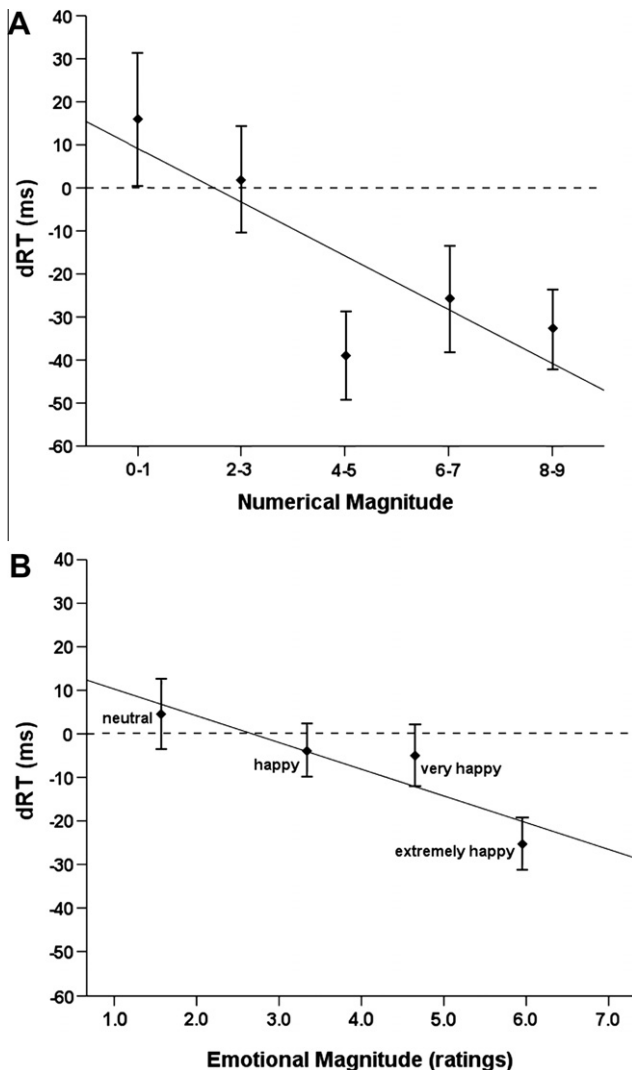
Fig. 2. Mean dRT (Y-axis: right RT minus left RT) in Experiment 1 for (A) pairs of numbers in the Number task, and (B) facial expressions in the Face task. Negative dRT values indicate faster right responses, and positive dRT values indicate faster left responses. Error bars are +/− SEM.

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[1] In the slope analysis for the Face task, dRT was calculated by participant, collapsing across the six face models. We also conducted an item analysis, in which dRT was calculated by face model, collapsing across participants; dRT values were regressed on the means of the EM ratings for each expression to produce an item-based slope. The average slope coefficient (M = -6.48 ms/EM) was significantly different from zero, $t(5) = 3.53$, $p = .02$, with a negative slope for each of the six models, showing that left-to-right orientation was consistent across models.

[2] Recent evidence from the SNARC paradigm with parity judgments (as in the Number task) suggests that left and right responses may be faster to odd and even numbers, respectively, because the adjectives left and odd are linguistically marked while right and even are linguistically unmarked (a MARC – linguistic markedness of response codes – effect; Nuerk, Iversen, & Willmes, 2004). A similar effect might be expected in the Face task, with female (marked) and male (unmarked) responses associated with left and right, respectively. However, when comparing RTs on congruent (Number task: right-even, left-odd; Face task: right-male, left-female) and incongruent (Number task: right-odd, left-even; Face task: right-female, left-male) trials, we found no evidence of MARC effects in any of the three experiments reported here (all $ps > .05$). Given that MARC effects have not always been replicated for numbers (e.g., Fischer, Warlop, Hill, & Fias, 2004), that they appear to be strongest for verbal stimuli (Nuerk et al., 2004), and that they often require less standard statistical analyses (for details, see Nuerk et al., 2004), the lack of effects in our experiments is not inconsistent with existing data.

as fast as judging gender for a mixed set of happy and fearful expressions; Atkinson, Tipples, Burt, & Young, 2005), the current findings suggest that such judgments are, at least to some extent, influenced by the *degree* (i.e., magnitude) of emotion. It appears, then, that people automatically extract magnitude relations from faces, mentally organizing this information in a spatial format.

An alternative explanation of our findings is that left-to-right orientation was due to specific facial features that varied across the range of stimuli, rather than the magnitude of emotional expression per se. This possibility seems unlikely, however, because features such as skin tone and amount of hair were held constant across all expressions for a given model (see Fig. 1). The one physical dimension that varied somewhat across expressions was the size of the mouth; more happy faces had a larger mouth opening than less happy faces. An explanation based on mouth size is challenged, however, by substantial evidence that faces are processed in a holistic fashion (for review, see Maurer, Le Grand, & Mondloch, 2002), and that, if anything, more attention tends to be directed to the eyes than to other parts of the face (e.g., Taylor, Edmonds, McCarthy, & Allison, 2001). Indeed, holistic processing of faces may support the extraction of emotional magnitude, which then comes to be spatially organized in the mind.

3. Experiment 2

Recent evidence suggests that emotion-related stimuli may be mentally represented in terms of valence, with negatively- and positively-valenced stimuli associated with the left and right sides of space, respectively (Root, Wong, & Kinsbourne, 2006), at least in right-handers (Casasanto, 2009). In Experiment 1, magnitude and valence were confounded; more happy faces were also more positive than less happy faces. As a consequence, left-to-right orientation might reflect mappings of valence, rather than magnitude. Indeed, on one account, continuous stimuli are mentally coded in binary terms (e.g., negative/positive) when processed spatially (e.g., with left and right response keys), with facilitation occurring when "dominant" codes (e.g., "positive" and "right") are aligned (Fitousi, Shaki, & Algom, 2009; Proctor & Cho, 2006). Experiment 2 was designed to disentangle magnitude and valence as possible factors driving the spatial organization of emotional expression.

As in Experiment 1, participants made gender judgments to faces by pressing left and right response keys, but here the range of faces included negative expressions (angry faces; see Fig. 1b) in addition to positive expressions (happy faces). On a magnitude account, faster right responses should be observed with greater emotional magnitude, regardless of the specific emotion; that is, with increasing happiness *or* angriness. In contrast, on a valence account, angrier (more negative) faces should produce faster left responses and happier (more positive) faces should produce faster right responses. For comparison, participants also completed the same Number task used in Experiment 1.

3.1. Method

3.1.1. Participants

Forty-six students (37 female) participated for course credit. The majority of participants (40) were right-handed (EHI: $M = 58$; range: −75 to 100). All had normal or corrected-to-normal vision and gave written consent to participate. Procedures were approved by the local ethics committee.

3.1.2. Stimuli and procedure

The Number task was identical to that of Experiment 1. In the Face task, both happy and angry expressions were included among the five facial expressions (labeled here *neutral*, *happy*, *angry*,

extremely happy, and *extremely angry*; see Fig. 1), for a total of 30 images. Each of two blocks consisted of 10 practice trials and 90 test trials (30 face stimuli presented three times each, with 18 trials of each expression). All other aspects of the procedure were identical to Experiment 1.

3.2. Results

3.2.1. Ratings of face stimuli

Ratings of emotional magnitude (EM; as in Experiment 1) and emotional valence (EV) were used to approximate psychological distance between facial expressions in the Face task. As in Experiment 1, a separate group of participants ($N = 10$) assigned EM ratings to each of the 30 face stimuli (random order). The same participants also assigned emotional valence (EV) ratings from 1 to 7 (1 = "very negative expression"; 4 = "neutral expression"; 7 = "very positive expression") to the same stimuli (task order counterbalanced). Mean EM ratings for the five expressions were 1.48 (*neutral*), 3.83 (*happy*), 4.80 (*angry*), 6.08 (*extremely happy*), and 6.22 (*extremely angry*). In both participant and item (face model) analyses of the EM rating data, all pairwise comparisons among the five expressions were statistically significant ($ps < .05$), except for the comparison between *extremely happy* and *extremely angry* ($ps > .3$), suggesting the following order of increasing magnitude: *neutral* < *happy* < *angry* < *extremely happy* = *extremely angry*. Mean EV ratings were 1.63 (*extremely angry*), 2.28 (*angry*), 3.63 (*neutral*), 5.13 (*happy*), and 6.58 (*extremely happy*). In both participant and item analyses of the EV rating data, all pairwise comparisons were statistically significant (all $ps < .01$), with the following order from negative to positive valence: *extremely angry* < *angry* < *neutral* < *happy* < *extremely happy*.

3.2.2. Slope analyses

Using Experiment 1 criteria, data from the two tasks were trimmed (Number task: 7.3% of trials excluded, with 4.6% incorrect; Face task: 4.9% of trials excluded, with 2.5% incorrect). Overall mean RTs on remaining trials were 595 ms ($SD = 148$) and 561 ms ($SD = 149$) in Number and Face tasks, respectively. As in Experiment 1, dRT values for each digit pair and facial expression were calculated for each participant. For the Number task, the mean slope coefficient was −4.19 ms/digit ($SD = 9.13$), replicating the results of Experiment 1 (and previous research), $t(45) = 3.12$, $p = .003$, $d = .46$. For the Face task, dRT values were regressed on mean EM and EV ratings to produce magnitude and valence slopes, respectively. The magnitude slope ($M = -6.51$ ms/EM, $SD = 20.51$) differed significantly from zero, $t(45) = 2.15$, $p = .04$, $d = .32$, and from the valence slope ($M = 1.61$ ms/EV, $SD = 12.33$), $t(45) = 2.09$, $p = .04$, $d = .48$, whereas the valence slope did not differ significantly from zero, $t(45) = .89$, $p = .38$.[3] As predicted by the magnitude account, right responses became faster with increasing emotional magnitude, whether expressions were happy or angry (see Fig. 3). The significant magnitude slope and non-significant valence slope suggest that left-to-right orientation was indiscriminate with respect to valence, and instead was driven by the magnitude relations among stimuli. A 2 [task: Number or Face (magnitude slope); within-subjects] × 2 (order of tasks; between-subjects) ANOVA on the slope data revealed no significant main effects or interaction ($ps > .5$), suggesting that the strength of spatial organization was comparable for number and emotional magnitude.

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[3] As in Experiment 1, item analyses converged with participant analyses. dRT in the Face task was calculated for each model and regressed on mean EM and EV ratings to produce item-based magnitude and valence slopes, respectively. The magnitude slope ($M = -6.77$ ms/EM) was significantly different from zero, $t(5) = 2.55$, $p = .05$, with a negative slope for five of the six models. The valence slope ($M = 1.69$ ms/EV) did not differ from zero, $t(5) = .77$, $p = .48$, with a positive slope for four of the six models.
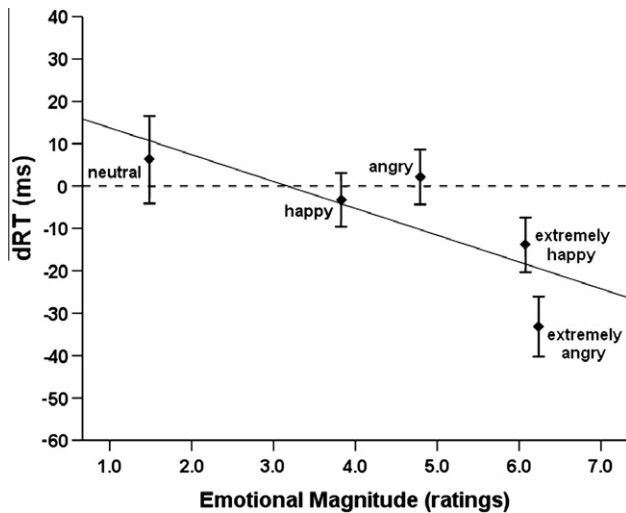
Fig. 3. Mean dRT for facial expressions in Experiment 2 on the Face task. Negative dRT values indicate faster right responses, and positive dRT values indicate faster left responses. Error bars are +/− SEM.

Correlation analyses revealed no statistical relation between number and emotional magnitude slopes ($r = -.04$, $p = .79$). While the lack of a significant positive correlation might appear inconsistent with a magnitude account, a comparison of number slopes in Experiments 1 and 2 suggests a possible explanation. The number slope in Experiment 2 (−4.19 ms/digit) was smaller than in Experiment 1 (−6.26 ms/digit), with nearly one quarter of participants in Experiment 2 (24%) showing a positive number slope. Correlations between numerical and emotional magnitude may depend on, and perhaps be driven by, reliable left-to-right orientation of number. Consistent with this possibility, participants with a negative slope coefficient on the Number task (i.e., left-to-right orientation) showed a significantly more positive correlation between number and emotional magnitude slopes than participants with a positive slope coefficient on the Number task (i.e., right-to-left orientation), Fisher $z = 2.31$, $p = .02$ (see Section 5.1 for further discussion and implications).

3.3. Discussion

The goal of Experiment 2 was to distinguish between magnitude and valence accounts of the spatial organization of emotional expression. The results were inconsistent with a valence account. Left and right sides of space were not associated with negative and positive emotion, respectively. Instead, greater emotion more generally, whether positive or negative, was represented as increasingly rightward. As shown in Fig. 3, the fastest right responses occurred for the most emotional faces (i.e., *extremely angry*), even though they were also the most negatively valenced. While valence is known to be highly salient during the processing of emotional facial expressions (Nakashima et al., 2008; Root et al., 2006), magnitude appears to be the determining factor in their spatial organization.[4]

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[4] Research by Casasanto (2009) suggests that handedness may modulate mappings between valence and space. Could the lack of an effect for valence in Experiment 2 be due to the composition of right- and left-handers in our sample? That is, did right-handers (but not left-handers) organize negative faces on the left and positive faces on the right? To address this possibility, we conducted slope analyses with left-handers (i.e., participants with negative EHI scores) excluded. In Experiment 2, the magnitude slope differed significantly from zero, $t(39) = 2.24$, $p = .03$, but the valence slope did not, $t(39) = .95$, $p > .3$, mirroring the results with the full sample and providing further evidence that magnitude, not valence, served as the basis for spatial organization. In Experiments 1 and 3, slope analyses (based on magnitude ratings) with left-handers excluded also remained significant (all $ps < .05$).

Experiment 2 included different emotions (i.e., happy and angry), but the observed pattern of left-to-right orientation seemed to reflect an undifferentiated scale of emotional magnitude spanning *less* to *more*. That is, *more* corresponded to "more emotional" and *less* to "less emotional," irrespective of the specific emotion. When not required to differentiate emotions, people may organize emotional expressions in terms of their overall magnitude. This type of undifferentiated processing may be quite common; for example, even rats appear to treat number and duration interchangeably, with 1 s approximately equal to a mental count of 5 (Meck & Church, 1983). In certain contexts, however, humans (and rats too) must reason exclusively within the parameters of a single dimension. For example, a doctor confronted with a room full of sick patients must decide which are the sickest in order to allocate his or her time appropriately. In making this decision, other magnitude cues (e.g., patients' height and weight, how long they have been waiting, the number of people accompanying them, etc.) may be irrelevant and, if so, should be ignored.

In the case of emotional expression, there are certain contexts in which undifferentiated processing would clearly be maladaptive. When someone is in a position to do harm, for example, it is critical that we identify how angry the threatening individual is, not simply how emotional. Undifferentiated processing, in which magnitude applies to overall emotion more generally (i.e., more/less emotion) can be contrasted with *differentiated* processing, in which it applies, for example, to angriness or happiness specifically (i.e., more/less angry or more/less happy). This distinction is suggestive of the well-known perceptual distinction between "overall similarity" and "dimensional identity" (Smith, 1989); that is, the processing of multidimensional stimuli as integrated wholes versus separable dimensions (see also Garner, 1974). A wealth of empirical evidence suggests that the relative salience of integrated wholes versus separable dimensions depends on factors such as the level of processing, the type of task, and contextual cues (e.g., Kemler-Nelson, 1989; Navon, 1977; Smith & Heise, 1992). When such factors highlight a specific emotion rather than the overall degree of emotion, the processing of emotional stimuli, and their underlying spatial organization, may change accordingly.

4. Experiment 3

When facial expressions are processed in differentiated terms (i.e., with respect to a specific emotion), what are the consequences for left-to-right orientation? One possibility is that left-to-right orientation accommodates to the relevant emotion. For example, when contextual demands promote thinking about emotion specifically in terms of happiness, angrier facial expressions may be regarded as *less* happy (as opposed to *more* angry), and left-to-right orientation might reflect this differentiation; that is, faster right responses with decreasing (rather than increasing) angriness. Experiment 3 examined the flexibility of left-to-right orientation in adjusting to the relational structure of a specific emotion (i.e., happiness or angriness).

As in Experiment 2, participants were presented with a range of both happy and angry faces, but here they made explicit judgments about one of the emotions specifically, designed to promote differentiated processing. Participants judged facial expressions on the basis of happiness (i.e., "happy" or "not happy" judgments) in the Happy task, and judged the same facial expressions on the basis of angriness (i.e., "angry" or "not angry" judgments) in the Angry task. We expected different patterns of spatial organization across the two tasks. Specifically, in the Happy task, right responses should become faster with increasing happiness (i.e., decreasing angriness); in contrast, in the Angry task, right responses should become faster with increasing angriness (i.e.,

deceasing happiness). Slopes across the two tasks should differ accordingly. If, however, left-to-right orientation reflects overall emotional magnitude exclusively (i.e., undifferentiated processing), the findings should mirror those of Experiment 2, with right responses becoming relatively faster with increasing happiness or angriness irrespective of the type of judgment; that is, more emotional faces (whether happy or angry) should elicit relatively faster right responses than less emotional faces, with no statistical difference between slopes for the two tasks.

4.1. Method

4.1.1. Participants

Twenty students (15 female) participated for course credit. The majority of participants (19) were right-handed (EHI: $M = 68$; range: −13 to 100). All had normal or corrected-to-normal vision and gave written consent to participate. Procedures were approved by the local ethics committee.

4.1.2. Stimuli and procedure

Stimuli were the same as in the Face task of Experiment 2, except that the *neutral* expression was omitted (since it is unlikely to be consistently judged as either happy or angry), leaving a total of 24 images. Each participant completed both Happy and Angry tasks (order counterbalanced). In the Happy task, participants judged whether each face was "happy" or "not happy" by pressing left and right response keys. In one block, "happy" responses were assigned to the left key and "not happy" responses to the right key; the other block used the reverse assignment (order counterbalanced). The Angry task was identical, except that the responses were "angry" or "not angry." Each task consisted of two blocks of trials, with 12 practice trials and 96 test trials per block. All other aspects of the procedure were identical to the Face task of Experiment 1.

4.2. Results

4.2.1. Ratings of face stimuli

Emotion-specific EM ratings for happiness and angriness were used to approximate psychological distance between facial expressions in terms of the specific emotions. A separate group of participants ($N = 10$) assigned both happiness and angriness ratings (separate blocks; order counterbalanced) to each of the 24 face stimuli (random order). For both sets of ratings, the scale ranged from 1 to 7 (happiness: 1 = "not at all happy," 7 = "extremely happy"; angriness: 1 = "not at all angry," 7 = "extremely angry"). Mean happiness ratings for the four expressions were 1.63 (*extremely angry*), 2.00 (*angry*), 4.57 (*happy*), and 6.43 (*extremely happy*). Mean angriness ratings were 1.08 (*extremely happy*), 1.73 (*happy*), 5.42 (*angry*), and 6.15 (*extremely angry*). Thus, the order of increasing emotional magnitude for happiness ratings (i.e., from *extremely angry* to *extremely happy*) was the reverse of that for angriness ratings (i.e., from *extremely happy* to *extremely angry*). For both sets of ratings, all pairwise comparisons among expressions were significant in participant analyses (all $ps < .05$), with the following order for happiness ratings: *extremely angry* < *angry* < *happy* < *extremely happy*; and for angriness ratings: *extremely happy* < *happy* < *angry* < *extremely angry*. In item analyses, all pairwise comparisons between expressions were significant ($ps < .0001$), except for the comparison between *extremely angry* and *angry* in both happiness ($p = .14$) and angriness ($p = .08$) ratings, although the difference was in the expected direction for both sets of ratings (i.e., the *extremely angry* expression was rated as less happy and more angry than the *angry* expression).
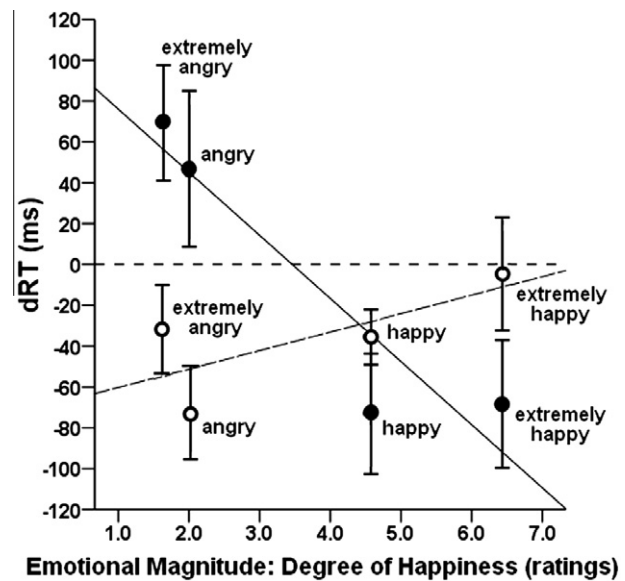

Fig. 4. Mean dRT for facial expressions in Experiment 3 on Happy (light circles; dashed regression line) and Angry (dark circles; solid regression line) tasks (first task completed only). Negative dRT values indicate faster right responses, and positive dRT values indicate faster left responses. Error bars are +/− SEM.

4.2.2. Slope analyses

Data from the Happy and Angry tasks were trimmed (Happy task: 7.8% of trials excluded, with 5.5% incorrect; Angry task: 8.2% of trials excluded, with 5.5% incorrect) according to the criteria used above. Mean RTs on remaining trials were 638 ms ($SD = 97$) and 676 ms ($SD = 133$) in Happy and Angry tasks, respectively. dRT values for each facial expression were calculated for each participant. These values were regressed on mean happiness and angriness ratings for each expression to produce slopes for each of the two tasks. Separate analyses were conducted on the slope data based on the two types of ratings.

4.2.3. Happiness ratings

For the slope data based on happiness ratings, a 2 (task: Happy or Angry; within-subjects) × 2 (order of tasks; between-subjects) ANOVA revealed a significant main effect of task order, $F(1, 18) = 7.88$, $p = .01$, but no interaction, $F(1, 18) = .01$, $p = .94$. Because of the significant order effect, we first consider performance on Happy and Angry tasks when each was the first task completed. In this analysis, there was a significant difference between the two tasks (Happy task: $M = -30.90$ ms/EM, $SD = 42.34$; Angry task: $M = 9.05$ ms/EM, $SD = 29.29$), $t(18) = 2.45$, $p = .03$, $d = 1.10$.[5] Left-to-right orientation was in terms of increasing happiness on the Happy task (negative slope) and decreasing happiness (i.e., increasing angriness; positive slope) on the Angry task. Consistent with these findings, right responses were significantly faster for the angriest faces (i.e., *extremely angry* and *angry*) on the Angry task compared to the Happy task, $t(38) = 3.53$, $p = .001$, and for the happiest faces (i.e., *extremely happy* and *happy*) on the Happy task compared to the Angry task, $t(38) = 1.83$, $p = .04$, one-tailed (see Fig. 4). Comparisons of the first and second tasks completed revealed that

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[5] As in the previous experiments, item analyses converged with participant analyses. dRTs in the Happy and Angry tasks were calculated for each model and regressed on mean EM happiness ratings to produce item-based slopes for both tasks. As in the participant analyses, the negative slope in the Happy task ($M = -30.77$ ms/EM) was significantly different from the positive slope in the Angry task ($M = 8.11$ ms/EM), $t(5) = 10.17$, $p < .001$. In addition, all six face models produced negative slopes in the Happy task and positive slopes in the Angry task, showing that the effects were consistent across models.

performance on the first task carried over to the second task (as suggested by the lack of an interaction between task and order), with no significant differences in slope between the two, either for participants who completed the Happy task first, $t(9) = .90$, $p = .39$, or the Angry task first, $t(9) = .89$, $p = .40$. Within participants, slopes on the Happy and Angry tasks were positively correlated ($r = .37$), a value approaching statistical significance ($p = .10$). This finding again suggests carryover from the first task to the second; participants who completed the Happy task first tended to show negative slopes on both tasks, whereas those who completed the Angry task first tended to show positive slopes on both tasks.

4.2.4. Angriness ratings

Results based on angriness ratings were the mirror opposite of those based on happiness ratings, as expected since the facial expressions were in reverse order across the two sets of ratings (see Ratings of face stimuli above). More specifically, in the Happy task, the slope was negative when based on happiness ratings but positive when based on angriness ratings; in the Angry task, the slope was positive when based on happiness ratings but negative when based on angriness ratings. For the slope data based on angriness ratings, a 2 (task) × 2 (order of tasks) ANOVA revealed a significant main effect of task order, $F(1, 18) = 8.33$, $p = .01$, but no interaction, $F(1, 18) = .01$, $p = .91$. For the first task completed, the positive slope in the Happy task ($M = 29.11$; $SD = 38.83$) was significantly different from the negative slope in the Angry task ($M = -6.88$; $SD = 24.75$), $t(18) = 2.47$, $p = .02$, $d = 1.11$. Carryover effects were again observed, with no significant differences in slope between the first and second tasks completed, either for participants who completed the Happy task first, $t(9) = .83$, $p = .43$, or the Angry task first, $t(9) = .74$, $p = .48$. As with the results based on happiness ratings, the positive correlation between slopes on the two tasks within participants, $r = .40$, $p = .08$, is further suggestive of carryover effects.

4.3. Discussion

The results of Experiment 3 suggest that when facial expressions are processed in terms of a specific emotion, the mental organization of emotional expression adjusts accordingly. Left-to-right orientation shifts from undifferentiated (the pattern observed in Experiment 2) to differentiated, or from more/less *emotional* (when no emotion is specified) to more/less *angry* or more/less *happy* (when the context-relevant emotion is angriness or happiness, respectively). While the first two experiments demonstrated that left-to-right orientation is shared across magnitude dimensions, the findings of Experiment 3 suggest that this organization is flexible. Just as in the example above in which the doctor's job demands that he or she isolate the dimension of sickness, certain contexts may highlight the more/less relations specific to a given emotion, and spatial organization appears to accommodate this new relational structure. Yet the carryover effects observed in this experiment are consistent with some representational stability, at least at the level of the specific emotion. Following the differentiated processing of emotional magnitude, left-to-right orientation may, at least temporarily, be resistant to restructuring. Future research might address how long the initial structure is maintained and the role of habitual experiences (e.g., language and cultural practices) in endorsing a particular structure over other plausible ways of mentally organizing the same information.

5. General discussion

The mental number line has been regarded as a useful metaphor for highlighting the spatial nature of numerical representation. The present research suggests, however, that number may have been overly privileged in this literature. Our findings of left-to-right orientation for emotional expression point to spatial organization as a property of magnitude representation that is far more general (see also Gallistel, 2011; Lourenco & Longo, 2011). Indeed, although we focused only on number and emotional expression, our findings suggest that left-to-right orientation may extend to any dimension that can be captured in terms of more/less relations. The implication is that vastly different cues to magnitude, whether prototypical or otherwise, share a common format of representation within the mind: a mental *magnitude* line.

5.1. A single spatial representation versus many

What is the nature of this shared representational format? One possibility is that a mental magnitude line exists as a single, monolithic representation, fully abstracted from any specific dimension. Proponents of this view would likely argue for strong correlations between left-to-right orientation for number and emotional expression, since each dimension should rely on some form of the same underlying representation. While the lack of strong correlations in Experiments 1 and 2 would seem to provide evidence against this view, there is reason to believe that the correlations could have been masked by task-related factors such as the type of judgment. Correlations between spatial extent and number have been reported on bisection tasks in which participants mark the center of physical lines or estimate the midpoint of numerical intervals (Longo & Lourenco, 2007, 2010). In these tasks, unlike those in Experiments 1 and 2, the response is an explicit magnitude judgment (i.e., marking "half" of a given interval) and is essentially the same across dimensions. Within the context of the SNARC paradigm, correlations might be more evident when magnitude is explicitly invoked (e.g., comparing the magnitude of a given number to that of a reference; Wood, Willmes, Nuerk, & Fischer, 2008) and hence use the same type of judgment to tap spatial organization across dimensions.

Another possibility, however, is that the lack of strong correlations in our experiments points to a system that is far more complex than a single magnitude line, with each dimension maintaining its own spatial format of representation (e.g., left-to-right *number*, left-to-right *emotion*, etc.). On this view, different dimensions would draw on the same left-to-right organizational template, but the representations themselves would be functionally distinct; that is, multiple magnitude lines, possibly one for each dimension. Relatedly, the findings of Experiment 2, in which number and emotional expression were more strongly correlated in participants with reliable left-to-right orientation of number, suggest that cross-dimension correlations might be driven specifically by number. That is, number might be psychologically prepotent, with other dimensions co-opting its representational structure. This possibility is supported by the prevalence of spatial depictions of number on cultural tools and artifacts (e.g., rulers and computer keyboards), which may reinforce left-to-right orientation for number over other dimensions.

At the neural level, a growing body of evidence suggests that different dimensions are subserved by both common and distinct brain regions in a distributed system encompassing both parietal and frontal areas (Bueti & Walsh, 2009; Cohen Kadosh et al., 2008; Nieder, 2005; Wencil, Radoeva, & Chatterjee, 2010). Within this system, less prototypical dimensions (e.g., emotional expression; see also Chiao et al., 2009) may be more functionally distinct and hence show less neural overlap than more prototypical dimensions (e.g., number and duration). Alternatively, there is evidence that specific neurons in parietal cortex encode multiple types of magnitude information (e.g., number and spatial extent; Tudusciuc & Nieder, 2007), suggesting highly abstract encoding of more/less

relations within select regions. Given that Arabic numerals and human faces are perceptually quite dissimilar, common neural encoding would be especially striking. As yet unknown, however, is precisely how the property of left-to-right orientation might be instantiated neurally. An intriguing possibility, suggested by evidence of neurons sensitive to both duration and spatial location (Leon & Shadlen, 2003), is that the same neurons that encode relative leftward and rightward positions in space might also be sensitive to stimuli denoting more/less relations. The representational commonalities observed in the present study suggest a need for more precise understanding of the extent to which different magnitude dimensions are subserved by the same, as opposed to neighboring or interconnected, neural regions.

5.2. Alternative accounts of spatial organization

A recent proposal suggests that the SNARC effect is the result of a strategic decision to map magnitude to space, rather than a reflection of representational structure (Fischer, 2006; see also van Dijck, Gevers, & Fias, 2009). On this account, individuals strategically assign numbers to the left–right axis within the particular context of the SNARC paradigm, and this processing can be adjusted by task demands and various forms of experience. Such a proposal might be extended to explain our findings with face stimuli. While we acknowledge the possibility of strategic processing in the current experiments, we would suggest that left-to-right orientation may nonetheless be a property of the representation itself. Further, by a common spatial format, we do not intend to suggest a static representation in which magnitude values occupy fixed, permanent locations in mental space. Indeed, the findings of Experiment 3 suggest otherwise (for evidence of flexibility in spatial organization of number, see Bächtold, Baumüller, & Brugger, 1998; Dehaene et al., 1993). Research in the grounded cognition tradition suggests a broader definition of *representation*, as a dynamic pattern of neural activity that is highly flexible and task-dependent (Barsalou, 2008). Thus, strategic processing, if any, need not imply a lack of representation.

Another alternative account asserts that spatial organization is not in fact spatial at all, but merely an epiphenomenon of stimulus–response (S–R) compatibility (Fitousi et al., 2009; Proctor & Cho, 2006). Some might argue that the findings of Experiment 2, while inconsistent with a valence-based explanation, could nevertheless reflect S–R mappings based on magnitude (i.e., "less emotion"/"more emotion" codes mapped to "left"/"right" codes). However, in the case of faces and other complex stimuli with multiple properties, the S–R account does not offer a priori predictions regarding which properties will be mapped (and which codes generated), much less predict that magnitude would trump other properties. Moreover, while S–R compatibility may be sufficient to explain effects observed in the canonical SNARC paradigm, many other robust space-magnitude links, such as the finding that numerical processing elicits shifts in spatial attention (Fischer et al., 2003; Salillas, El Yagoubi, & Semenza, 2008), are not easily explained by this account. We thus suggest that the format of representation explored in the present experiments reflects organization within mental space rather than correspondences between binary codes, although future research would benefit from efforts to differentiate these accounts empirically.

5.3. Potential functions of spatial organization

As a ready template for representing magnitude, space may allow for the offloading of cognitive resources otherwise devoted to maintaining fine-grained magnitude distinctions in memory (cf. Goldin-Meadow & Beilock, 2010). Indeed, we would suggest that a consistent spatial orientation may also be useful for establishing

long-term memory representations for later access and manipulation (see also Thompson & Siegler, 2010). In Experiment 3, we observed that left-to-right orientation of emotional expression was sufficiently flexible to adjust to specific emotions, but, as shown by the carryover effects from one task to the next, an initial structure can be retained even under conditions designed to promote reorganization. Although this representational stability might be inconsistent with complete flexibility, it may avoid the processing costs associated with switching between conflicting representations (e.g., Monsell, 2003). Our findings are consistent with the idea that mental space may function to establish coherently structured, yet sufficiently adaptable, representations of relatively abstract types of information (Gattis, 2001; Lakoff & Johnson, 1980).

More/less relations initially come to us in the form of cues gleaned from the senses, from which magnitude must be abstracted. Our findings suggest that such abstraction occurs spontaneously, supporting inferences about everything from the approximate number of jelly beans in a jar to the rough amount of emotion expressed in a face. Thus, representational space may serve to instantiate abstract relational notions of "more" and "less," regardless of the particular form or modality by which they are accessed. In this way, the cognitive resources used in organizing numerical magnitude may be shared or recycled for use with a myriad of other types of magnitude – a type of neural or conceptual economy (cf. Dehaene, 2005; Dehaene & Cohen, 2007). Conceptualizing more/less relations via a mental magnitude line may be one way for the mind to make sense of the seemingly intangible.

Acknowledgments

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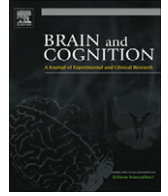
Corrigendum

Corrigendum to "Common spatial organization of number and emotional expression: A mental magnitude line" [Brain and Cognition 77 (2011) 315–323]

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In the caption to Fig. 4, the first sentence labels the Happy and Angry tasks incorrectly. The sentence should read: "Mean dRT for facial expressions in Experiment 3 on Happy (dark circles; solid regression line) and Angry (light circles; dashed regression line) tasks (first task completed only)."