

Supplementary Information

To accompany

Increasing verbal knowledge mediates development
of multidimensional emotion representations

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Supplementary Notes

Supplementary Note 1: Analyses of valence focus

Here we present analyses of valence focus (i.e., the weight participants placed on the first dimension of emotion in the semantic similarities task). A robust regression revealed that valence focus decreased significantly across age, $\beta = -.38, p < .001$. Unlike for arousal focus, a robust bootstrapped mediation with 10,000 resamples revealed that valence focus did not mediate increases in emotional bidimensionality across age, indirect effect $\beta = .10, 95\% \text{ CI} = [-.01, .32], 27.25\%$ mediated.

Valence focus was significantly related to verbal knowledge, $\beta = -.42, p < .001$ and fluid reasoning, $\beta = -.31, p = .002$, and it shared a non-significant trending relationship with size focus (i.e., weight placed on the first dimension of the perceptual similarities control task), $\beta = .20, p = .069$. The direction of these effects indicate that reduced attention to valence was associated with increased verbal knowledge, increased fluid reasoning and reduced attention to the first dimension of the perceptual control task. However, a parallel robust mediation analysis of the relationship between valence focus and age (similar to **Figure 4a**) revealed that neither verbal knowledge, indirect effect $\beta = -.15, 95\% \text{ CI} = [-.35, .005], 24.26\%$ mediated, fluid reasoning, $\beta = -.07, 95\% \text{ CI} = [-.23, .01], 11.74\%$ mediated, nor size focus, $\beta = -.01, 95\% \text{ CI} = [-.08, .06], 1.62\%$ mediated, explained reduced valence focus across age. Unsurprisingly, the sequential mediation assessing whether verbal knowledge mediated increased emotional bidimensionality via valence focus (similar to **Figure 4b**) was not significant, $\beta = .05, 95\% \text{ CI} = [-.008, .21], 15.69\%$ mediated.

Supplementary Note 2: Analyses including participants who showed only some recognition of emotion terms

Here we present analyses that include 109 participants who had usable data for all tasks and demonstrated some—but incomplete—knowledge of emotion terms used in the task (i.e., those who received at least scores of 1 on all 10 emotion words used in the semantic similarities task, age range = 6.24-25.91, $M_{\text{age}} = 15.33$, $SD_{\text{age}} = 5.17$, 47.71% female, 57.80% Caucasian, 2 did not disclose race).

Even when including participants who did not achieve perfect vocabulary scores, MDS analyses of the semantic similarities task revealed that emotion representations were organized around valence and arousal axes (stress = .26, **Supplementary Figure 1**). Additionally, valence focus decreased with age, $\beta = -.29$, $p = .002$, arousal focus increased with age, $\beta = .36$, $p < .001$, emotional bidimensionality increased with age, $\beta = .24$, $p = .007$, and arousal focus significantly mediated the relationship between age and emotional bidimensionality, indirect effect $\beta = .29$, 95% CI = [.13, .53], 55.10% mediated. Replicating results in this augmented dataset further supports the claim that emotion concept representation becomes increasingly multi-dimensional across development.

In the extended dataset, all potential mediators significantly increased with age: Verbal knowledge, $\beta = .69$, $p < .001$, fluid reasoning, $\beta = .48$, $p < .001$, shading focus, $\beta = .24$, $p = .008$, and perceptual bidimensionality, $\beta = .22$, $p = .008$. Arousal focus shared significant positive relationships with verbal knowledge, $\beta = .44$, $p < .001$, fluid reasoning, $\beta = .37$, $p < .001$, and shading focus, $\beta = .25$, $p = .006$. Similarly, emotional bidimensionality was significantly related to verbal knowledge, $\beta = .29$, $p = .001$, fluid reasoning, $\beta = .26$, $p = .007$, and perceptual bidimensionality, $\beta = .19$, $p = .017$. However, a robust parallel mediation analysis in this

expanded dataset suggested that changes in arousal focus across age were not mediated by developments in verbal knowledge, indirect effect $\beta = .16$, 95% CI = [-.006, .35], 25.50% mediated, fluid reasoning, $\beta = .08$, 95% CI = [-.02, .24], 12.54% mediated, or shading focus, $\beta = .02$, 95% CI = [-.02, .09], 3.05% mediated. The development of emotional bidimensionality was also not mediated by verbal knowledge, indirect effect $\beta = .08$, 95% CI = [-.08, .25], 20.27% mediated, fluid reasoning, $\beta = .04$, 95% CI = [-.06, .22], 11.82% mediated, or perceptual bidimensionality, $\beta = .02$, 95% CI = [-.02, .08], 4.22% mediated. Because none of the mediators in the parallel mediation analysis significantly explained increased arousal focus across age, we were not justified to conduct the sequential mediation. Hence, the role of verbal knowledge in emotion concept development was only observable within those who demonstrated full knowledge of emotions used in tasks assessing emotion concept representation.

There was no evidence of a cohort-related intelligence confound in the expanded dataset. Robust regressions revealed no significant relations between age and full-scale IQ, $\beta = -.06$, $p = .559$, verbal knowledge T-scores, $\beta = -.02$, $p = .852$, or fluid reasoning T-scores, $\beta = -.06$, $p = .567$.

Supplementary Note 3: Emotion vocabulary assessment scoring guide

Definitions below are based on: Merriam-Webster dictionary for adults, Merriam-Webster dictionary for children, Oxford American Dictionary, and Google Dictionary. Synonyms are taken from a variety of sources. These definitions are only to serve as a rough guide in your scoring.

Angry. Definition: strong feeling of being upset, annoyed, displeased, or hostile.
Synonyms: irate, mad, annoyed, cross, vexed, irritated, indignant, irked, furious, enraged,

infuriated, in a temper, displeasure, fury, aggravated, livid; ticked off, pissed off; losing one's temper.

Annoyed. Definition: slightly angry; irritated. Synonyms: irritated, vexed, angry, exasperated, irked, get on someone's nerves, ruffle someone's feathers...

Amazed. Definition: surprised greatly; confused; filled with wonder; filled with astonishment. Synonyms: astonished, astounded, surprised, stun, stagger, shock, stupefy, awe, stop someone in their tracks, leave open-mouthed, leave aghast, take someone's breath away...

Bored. Definition: weary or restless because one is unoccupied or lacks interest in one's current activity. Synonyms: disinterested, dull, sick and tired, fatigued, blasé, spiritless, tired, inattentive, turned off.

Calm. Definition: in a quiet and peaceful state or condition; not feeling or showing nervousness, anger or other emotions. Synonyms: serene, tranquil, relaxed, unruffled, unperturbed, unflustered, untroubled...

Disappointed. Definition: sad, unhappy, or displeased because someone or something has failed to fulfill one's hopes or expectations. Synonyms: upset, saddened, let down, cast down, disheartened, downhearted, downcast, depressed, dispirited, discouraged, despondent, dismayed, distressed.

Disgusted. Definition: a strong feeling of dislike for something that has a very unpleasant appearance, taste, smell, etc.; annoyance and anger that you feel toward some behavior that is not good, fair, appropriate; revulsion or profound disapproval. Synonyms: revolt, repel, repulse, sicken, nauseate, turn someone's stomach.

Embarrassed. Definition: confused and foolish in front of other people; self-consciousness, shame, or awkwardness. Synonyms: mortified, red-faced, blushing, abashed,

shamed, ashamed, humiliated, awkward, self-conscious, uncomfortable...

Excited. Definition: eager enthusiasm and interest. Synonyms: thrilled, exhilarated, animated, enlivened, electrified.

Grumpy. Definition: easily annoyed or angered; having a bad temper or complaining often; sulky. Synonyms: crabby, ill-tempered, short-tempered, crotchety, testy, irritable, prickly, grouchy, snappy, cranky, irritable.

Happy. Definition: pleasure and enjoyment because of life, situation, etc.; contentment. Synonyms: cheerful, cheery, merry, joyful, jovial, jolly, jocular, gleeful, delighted, untroubled, smiling, beaming, grinning, in good spirits, in a good mood, lighthearted, pleased, content, satisfied, gratified, sunny, joyous.

Hate. Definition: intense or passionate dislike (for someone); have a strong aversion to (something). Synonyms: loathe, detest, despise, dislike, abhor, repelled by...

Jealous. Definition: intolerant of rivalry or unfaithfulness; envy of someone or their achievements and advantages. Synonyms: envious, covetous, desirous.

Lonely. Definition: sad from being apart from other people; sad because one has no friends or company; solitary. Synonyms: isolated, alone, lonesome, friendless, with no one to turn to, abandoned, rejected, unloved, unwanted, outcast, gloomy, sad, depressed, desolate, forsaken.

Love. Definition: strong or constant affection for a person; feel a deep romantic or sexual attachment to someone. Synonyms: deep affection, fondness, tenderness, warmth, intimacy, attachment, endearment, care very much for, hold very dear, adore, think the world of, be devoted to, dote on, worship.

Nervous. Definition: worried and afraid about what might happen; easily agitated or

alarmed; tending to be anxious; highly strung. Synonyms: high-strung, anxious, edgy, tense, excitable, jumpy, skittish, brittle, neurotic.

Pleased. Definition: happy or satisfied. Synonyms: happy, glad, delighted, grateful, thankful, content, satisfied.

Proud. Definition: deep pleasure, satisfaction, or happiness as a result of one's own achievements, qualities, or possessions or those of someone with whom one is closely associated; attitude or people who think that they are better or more important than others. Synonyms: pleased, glad, happy, delighted, joyful overjoyed, thrilled, satisfied, gratified, content.

Relaxed. Definition: calm and free from stress, worry, or anxiety; free from tension and anxiety; at ease. Synonyms: comfy, cozy, relaxed, content, satisfied, peaceful, resting, easygoing, undisturbed.

Sad. Definition: grief or unhappiness; sorrow. Synonyms: unhappy, sorrowful, dejected, depressed, downcast, miserable, down, blue, down in the dumps, blah.

Safe. Definition: free from harm or risk; secure from threat of danger, harm, or loss. Synonyms: secure, protected, shielded, sheltered, guarded, out of harm's way.

Scared. Definition: afraid of something; nervous, frightened, fearful. Synonyms: afraid, startled, nervous, fearful, panicky, alarmed, intimidated, terrified, petrified, terrorized, spooked.

Sorry. Definition: sorrow or regret; distress, especially through sympathy with someone else's misfortune. Synonyms: sad, unhappy, sorrowful, distressed, upset, downcast, downhearted, despondent.

Surprised. Definition: feelings caused by something that is unexpected or unusual. Synonyms: amaze, astonish, astound, dumbfounded, shocked, startled.

Thankful. Definition: glad that something has happened or not happened, that something or someone exists, etc. pleased and relieved; gratitude. Synonyms: grateful, appreciative, filled with gratitude, relieved.

Upset. Definition: unhappy, worried; disappointed. Synonyms: distress, trouble, unsettled, worried, bothered, agitated, hurt, sadden, grieve, perturbed, disquieted.

Worried. Definition: fear or concern because you think that something bad has happened or could happen; anxious, upset, or troubled about actual or potential problems. Synonyms: anxious, perturbed, troubles, bothered, concerned, upset, distressed, uneasy, agitated, nervous, edgy, tense, keyed up, jumpy, stressed, strung out.

Supplementary Note 4: Analyses of word sort task

In this task, participants sorted emotion words into piles based on similarity. Participants could make as many or as few piles as they wished, although piles must have fit on a 19.5" × 25.5" poster. Sorting was self-paced. This task provided a more unstructured assessment of how participants represent emotion concepts. We applied multidimensional scaling (MDS) analyses to participants' behavior on this task, following prior work.¹ For each participant, we produced a dissimilarity matrix that represented their groupings in the task. If two emotion words were put in the same pile, the value representing the dissimilarity between these emotions was 0. If they were not in the same pile, this value was 1. We then applied the INDSCAL procedure to participants' dissimilarity matrices and extracted the sample-level representation of emotions in this task, and participant-level valence focus, arousal focus, and emotional bidimensionality measures, similar to analyses of the semantic similarities task. Importantly, we performed these measures twice: once only including sort data from the 10 emotions used in the semantic

similarities task (same participant details as in the manuscript) and once including sort data from all 27 emotions (for this analysis, we excluded 20 participants who did not score 2 for all 27 words in the emotion vocabulary test, leaving 72 usable participants, age range = 7.89-25.91, $M_{\text{age}} = 16.26$, $SD_{\text{age}} = 4.64$, 54.17% female, 56.94% Caucasian, 2 did not disclose race).

A two-dimensional INDSCAL analysis (stress = .05) of sort data including only the 10 emotion words used in the semantic similarities task largely replicated the emotion organization found in the semantic similarities task (**Supplementary Figure 2**). Again, negative emotions (e.g., angry, scared, upset) were to the left of positive emotions (e.g., excited, happy, calm) suggesting that the horizontal dimension represented valence, and activating emotions (e.g., angry, scared, excited, surprised) were above deactivating emotions (e.g., calm, sad) suggesting that the vertical dimension represented arousal. Although subtle differences between the circumplex solutions for these two tasks emerged, Pearson's correlations of the coordinate positions of emotions for each task revealed extremely strong inter-task consistency in the positioning of emotions along the valence dimension, $r(8) = .95$, $p < .001$, and moderate consistency along the arousal dimension, $r(8) = .53$, $p = .117$.

However, robust regressions revealed that age was not significantly associated with valence focus, $\beta = -.07$, $p = .315$, arousal focus, $\beta = .12$, $p = .244$, or emotional bidimensionality, $\beta = .04$, $p = .737$, in this task. These measures were also not significantly related to any potential mediators, $ps > .356$ (except arousal focus shared a trending relationship with verbal knowledge, $\beta = .18$, $p = .069$). Hence, we did not conduct mediation analyses because these crucial relationships did not emerge at conventional levels of significance.

When analyzing all 27 emotions in the word sort task, a two-dimensional INDSCAL analysis (stress = .07) produced dimensions that appeared to represent valence and dominance,

rather than valence and arousal. Early studies on emotion representation proposed 3 primary dimensions: valence, arousal, and dominance,^{2,3} where dominance referred to how strongly an emotion motivates people to approach or dominate their environment (e.g., anger) vs. retreat from or be dominated by their environment (e.g., fear). Although the primary dimension of this model appeared to represent valence, the second dimension appeared to track dominance instead of arousal, as extreme emotions ranged from anger-like emotions (e.g., hate, angry, annoyed, grumpy) to fear-like emotions (e.g., scared, worried, nervous). This was not surprising, given that the order of affective dimensions is determined by the set of emotions being rated, and this set included many fear-like and anger-like emotions (i.e., hate, annoyed, grumpy, anger, worried, scared, and nervous), which would have forced participants to place greater emphasis on separating these emotions by dominance.

Consequently, we fit a three-dimensional INDSCAL analysis (stress = .05) of sort data from all 27 emotion words to examine whether the third dimension tracked arousal. Indeed, this appeared to be the case. **Supplementary Figure 3a** shows emotions spread along dimension 1 (valence) and dimension 2 (dominance), and **Supplementary Figure 3b** shows emotions spread along dimension 1 (valence) and dimension 3 (arousal) from the three-dimensional model. The valence dimension ranges from negative to positive emotions, the dominance dimension ranges from fear-like to anger-like emotions for negative emotions (with little spread within positive emotions), and the arousal dimension ranges from deactivating to activating emotions.

We extracted participants' weights for each of these dimensions (called valence focus, dominance focus, and arousal focus, respectively) and analyzed their relations with age. Results were identical to the 10-word analyses: Age was not significantly related to valence focus, $\beta = -.02$, $p = .763$, or arousal focus, $\beta = -.02$, $p = .833$, within the 27-word word sort task. Dominance

focus was also not significantly related to age, $\beta = .06, p = .626$. We computed the *bidimensionality* of emotion representations in this task along the valence and arousal dimensions following the same procedure as for the 10-emotion word sort and the semantic similarity task (see **Methods**). Emotion bidimensionality was also not significantly related to age, $\beta = -.05, p = .681$. Because valence focus and arousal focus were not significantly related to any potential mediators, $ps > .486$, we did not conduct mediation analyses.

Although this task replicated the emotion concept representations found in prior work and in our semantic similarities task data, we did not observe age-related changes in valence and arousal focus within this task. We report results from this task nonetheless for full scientific transparency and believe there are several potential reasons for this divergence that could be useful to future researchers. Although the word sort task may allow researchers to observe sample-level emotion representations, it may be a less sensitive assessment of the weight participants place on each dimension of these representations. In this task, dissimilarity matrices only include very rough estimates of how individual participants represent emotions (i.e., the values are either 0 or 1, whereas values in the semantic similarity task are decimals ranging from 0 to 1). Hence, MDS analyses of word sort data may be able to produce reliable sample-level configurations when combining dissimilarity matrices across many participants, but it may struggle to produce a strong estimate of individual participants' representations. This would result in weak estimates of participants' valence and arousal focus.

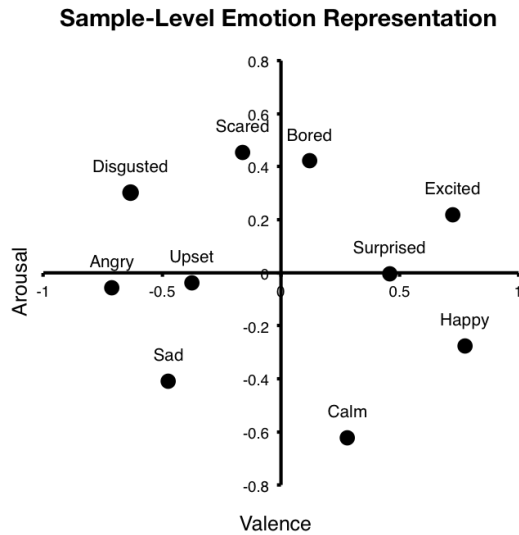
Prior researchers have combatted this problem by asking participants to sort the emotions several times into a prescribed number of piles each time.¹ This approach allows researchers to compute more specific estimates of emotion representation by averaging emotions' grouping across trials, which allowed the values in dissimilarity matrices to vary beyond just 0s and 1s.

We did not utilize this design because we were interested in participants' behavior when they were allowed to freely sort emotions into as many piles as they wished. Hence, future researchers are advised that repeated sorting into a specified number of piles may be a critical step for creating accurate participant-level estimates of emotion representation.

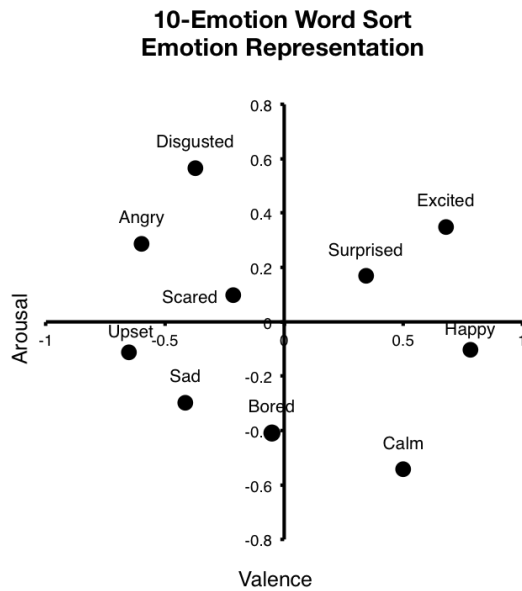
Supplementary Note 5: Perceptual similarities task MDS configurations

Even though a pilot sample suggested that participants could reproduce the two dimensions of size and shading in this task, the group INDSCAL solution in the final sample “collapsed” into a U shape rather than a circumplex (**Supplementary Figure 4**). This collapse arose because participants rated the fully white circle and the fully black circle as more similar than expected, potentially because they both involve an absence of shading. However, when we excluded the white circle, we recovered the 2 dimensions of size and shading imbued in the stimuli. We present analyses obtained from dissimilarity matrices that exclude the white circle because it was crucial that dimension weights tracked the actual dimensions inscribed in the stimuli.

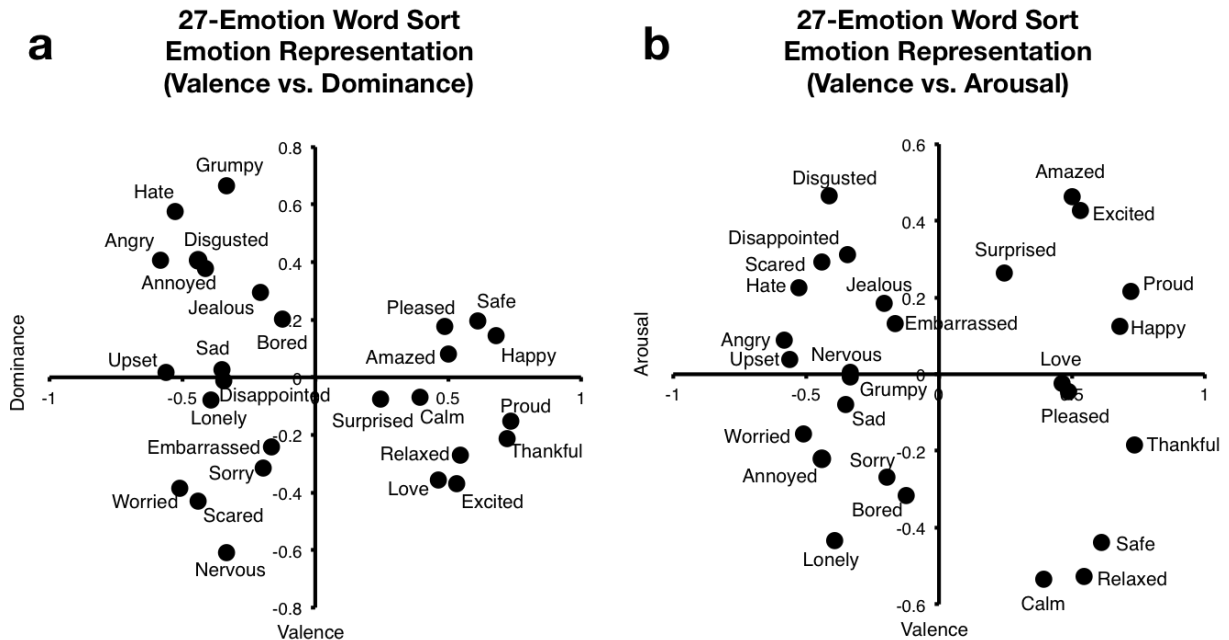
Supplementary Figures



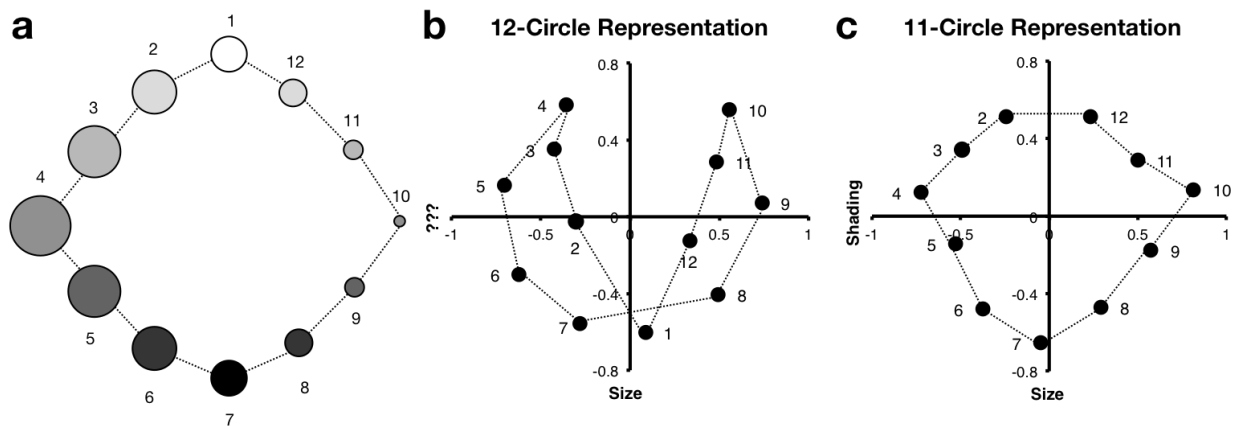
Supplementary Figure 1. Sample-level emotion representation within the semantic similarities task including data from those who demonstrated some—though incomplete—knowledge of emotion words.



Supplementary Figure 2. Sample-level organization of emotions within the 10-emotion subset of the word sort task.



Supplementary Figure 3. Sample-level organization of emotions including all 27 emotions in the word sort task. a) Emotions organized by the first (valence) and second (dominance) dimensions. b) Emotions organized by the first (valence) and third (arousal) dimensions.



Supplementary Figure 4. Sample-level representation of perceptual stimuli, as revealed by MDS analyses of participants' behavior in the circle similarity task. a) Stimuli used in the task, numbered to correspond to points in panels b and c. Dotted lines added to depict the intended representation of stimuli along the two dimensions of size (horizontal axis) and shading (vertical axis). b) Sample-level representation of all 12 circles in this task. Note how circle 1 has "collapsed" to be near circle 7, disrupting the intended meaning of the second dimension. c) Sample-level representation of circles in this task after removing circle 1. Note how axes return to the meaningful dimensions of size and shading.

Supplementary References

1. Russell, J. A. & Ridgeway, D. Dimensions underlying children's emotion concepts. *Dev. Psychol.* **19**, 795–804 (1983).
2. Russell, J. A. & Mehrabian, A. Evidence for a three factor theory of emotions. *J. Res. Pers.* **11**, 273–294 (1977).
3. Russell, J. A. & Steiger, J. H. The structure in persons' implicit taxonomy of emotions. *J. Res. Pers.* **16**, 447–469 (1982).