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Increasing verbal knowledge mediates development of multidimensional emotion representations

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How do people represent their own and others' emotional experiences? Contemporary emotion theories and growing evidence suggest that the conceptual representation of emotion plays a central role in how people understand the emotions both they and other people feel[1–6]. Although decades of research indicate that adults typically represent emotion concepts as multidimensional, with valence (positive–negative) and arousal (activating–deactivating) as two primary dimensions[7–10], little is known about how this bidimensional (or circumplex) representation arises[11]. Here we show that emotion representations develop from a monodimensional focus on valence to a bidimensional focus on both valence and arousal from age 6 to age 25. We investigated potential mechanisms underlying this effect and found that increasing verbal knowledge mediated the development of emotion representation over and above three other potential mediators: fluid reasoning, the general ability to represent non-emotional stimuli bidimensionally and task-related behaviours (for example, using extreme ends of rating scales). These results indicate that verbal development aids the expansion of emotion concept representations (and potentially emotional experiences) from a 'positive or negative' dichotomy in childhood to a multidimensional organization in adulthood.

An emotion concept is an individual's internal representation of what defines any given emotion[1,12,13]. Emotion concepts are attached to emotion words, and these words are thought to help organize the semantic knowledge of a given emotion (for example, its cognitive and contextual causes, body sensations, prototypical facial expressions and behavioural consequences)[5]. Contemporary theories and emerging evidence suggest that emotion concepts shape how individuals 'construct' both emotion perceptions (that is, inferences of how other people are feeling) and emotional experiences (inferences of how the individuals themselves are feeling)[1–6].

Although little work has explored the development of emotion concepts themselves, researchers have explored developmental trajectories of both emotion perceptions and emotion experiences. Young children around age 3.5 categorize facial expressions primarily into two groups corresponding to a 'positive versus negative' dichotomy, which gradually separates into more specific emotion categories over the following few years[14]. Hence, young children attend primarily to the valence of emotional expressions in others and learn to separate expressions based on other qualities—such as arousal—as they develop. Interestingly, young children's affective experiences may also be dichotomized into positive and negative categories. Children tend to experience negative emotions as wholly separate from positive emotions and only begin to report simultaneously experiencing both positive and negative emotions around age 8 (refs [15,16]). In fact, children show limited understanding that other people can experience both positive and negative emotions simultaneously until around age 11 (refs [17–19]). Hence, compared with adults, children place excess emphasis on valence and reduced emphasis on other affective dimensions when understanding both their own and others' emotions.

Constructionist theories would posit that this developmental trend could be explained by an underlying development in emotion concepts[1]. Specifically, from childhood to adulthood, emotion concepts may evolve from a positive–negative dichotomy into full multidimensional representations, and this shift may produce concomitant shifts in both emotional experiences and perceptions. Prior work has demonstrated that valence and arousal dimensions underlie young children's emotion representations (both for abstract concepts[20] and facial expressions[21,22]), and that children aged 7–11 report on their arousal in ways that appear similar to adults[23]. However, these studies did not test whether the weights that people place on the valence and arousal dimensions of emotions vary continuously from childhood to adulthood. Hence, the development of emotion concepts themselves remains unclear. Investigating this question is crucial for refining theoretical models of how people understand their own and others' emotions across development. Additionally, the specificity with which people parse their emotions (called emotion granularity or emotion differentiation) is associated with several indices of mental health in adulthood, including the absence of affective disorders and more adaptive emotion regulation[24]. Hence, insight into how emotion concepts develop may shed light on the origin of these individual differences and potentially aid early detection of later psychopathology[25]. Here, we directly assessed the development of emotion concept representations as well as mechanisms through which these representations evolve. We focused on four potential mediators identified in extant literature: verbal knowledge, fluid reasoning, the general ability to represent stimuli bidimensionally, and low-level task behaviours (for example, using extremes of rating scales).

Recent theoretical and empirical work indicates that increasing sophistication in one's verbal repertoire across development[26,27] may foster emotion concept development. The presence of linguistic labels aids one's ability to learn new conceptual distinctions,

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includingdistinctions between emotions[28,29]. Increasing verbal knowledge with age may therefore provide the linguistic footholds needed to create nuanced and distinct concepts for emotions, allowing people to break free from a valence-bound positive–negative emotional dichotomy. Indeed, prior work demonstrates that developments in verbal knowledge contribute to the development of 'emotion understanding' (that is, one's understanding of the myriad psychological processes involved in the production, experience, display and regulation of emotions)[18,30–32]. We tested whether verbal knowledge likewise fosters the development of multidimensional emotion representations.

It is also possible that general intellectual development—not verbal knowledge in particular—may drive emotion concept development. Common measures conceptualize verbal knowledge and fluid reasoning as separate components of intellectual ability[33]. Fluid reasoning refers to the ability to flexibly deduce and apply rules to solve new problems, and prior work indicates that this skill may also contribute to emotion concept development[31]. Hence, we tested the specificity of the relationship between verbal knowledge and emotion concept development by also assessing how emotion concept development relates to fluid reasoning.

The development of multidimensional emotion representations could also scaffold on development of the general ability to represent multiple dimensions simultaneously. Piagetian theory postulates that children tend to fixate on a single concrete perceptual dimension and neglect other dimensions, a phenomenon called centration[34]. Empirical studies demonstrate that people gradually develop an understanding that stimuli can have multiple dimensions as they age. For example, children tend to organize and represent animal species primarily in terms of their size, but these representations develop to include the more abstract dimensions of domesticity and predativity across adolescence and into adulthood[35]. Because representations of animals grow increasingly multidimensional across development, it is possible that multidimensional emotion representations arise through a similar domain-general cognitive developmental process.

Finally, there is evidence that children tend to behave differently from adults when using rating scales (for example, using the endpoints of the scale more than intermediary responses)[15,36]. This and other potential low-level task behaviours may inadvertently produce systematic variation in dependent variables across development. We empirically addressed this possibility through a control task that used a similar rating scale to our primary dependent variable.

In the present study, participants ($N=116$) aged 6–25 completed assessments of their conceptual representation of emotions, verbal knowledge and fluid reasoning, as well as a perceptual similarities control task and an emotion vocabulary test. Primary analyses include data from 92 participants who demonstrated full understanding of emotion words used in behavioural tasks. We intentionally chose a broad age range because most studies on emotion development are constrained to childhood or early adolescence (that is, up to age 12). As such, little is known about the full trajectory of affective development from childhood, though adolescence, into adulthood, even though adolescence is a period of dramatic changes in social and emotional processes[11]. We hypothesized (1) that the salience of the arousal dimension would increase with age, producing more bidimensional emotion representations at older ages and (2) that this shift would be most strongly explained by developments in verbal knowledge.

The semantic similarities task (adapted from prior work)[9,37] served as the primary assessment of emotion concept development. Participants rated the similarities of all possible pairwise combinations of ten emotion words on a continuous scale (Fig. 1a,b). INDSCAL multidimensional scaling techniques were used to extract both subject-level and sample-level emotion concept representations from these similarity ratings (see Methods). The sample-level emotion concept representation conformed to the circumplex model of emotions: primary dimensions underlying participants' similarity judgements were valence and arousal (Fig. 2a). On the first (horizontal) axis, negative emotions (such as disgusted, angry, sad) were to the left of positive emotions (such as excited, happy, calm), suggesting that this axis represented valence. On the second (vertical) axis, activating emotions (for example scared and excited) were above deactivating emotions (such as sad and calm), suggesting that this axis represented arousal.

Multidimensional scaling methods were also used to quantify the 'weight' that participants placed on the valence versus the arousal dimensions (called valence focus and arousal focus, respectively). As hypothesized, robust regressions revealed that valence focus decreased with age (beta value $\beta=-0.38$, $P<0.001$), and arousal focus increased with age ($\beta=0.44$, $P<0.001$) (Fig. 3a). We focus on age-related changes in arousal focus (that is, the addition of a second dimension beyond valence) and present analyses of valence focus in Supplementary Note 1. All regressions (including those in single mediation models) were robust to prevent undue influence from single points.

To verify that the prior result did not merely indicate that emotion representations shifted from a monodimensional focus on valence to a monodimensional focus on arousal, we computed the bidimensionality of participants' emotion representation by computing the difference between the horizontal and vertical width of their individual emotion representations (more negative = more monodimensional, 0 = equal spread along each dimension). This measure of emotional bidimensionality also increased with age ($\beta=0.27$, $P=0.003$) (Fig. 3b). Figure 2b,c visualizes these results by depicting how emotion concept representations shifted with age. To test the hypothesis that the addition of arousal focus across age led to more multidimensional emotion representations in adulthood, we conducted a robust bootstrapped mediation with 10,000 resamples and found that increases in arousal focus significantly mediated the increase in emotional bidimensionality with age (Fig. 3c). This mediation remained significant when including participants who showed only partial comprehension of the relevant emotions (that is, those who scored at least 1 out of 2 points for all ten words on the emotion vocabulary test; see Supplementary Note 2). Changes in valence focus did not mediate the development of emotional bidimensionality across age (see Supplementary Note 1).

Three additional tasks assessed potential mediators of emotion concept development. Unscaled scores from the Wechsler Abbreviated Scale of Intelligence (WASI-II) vocabulary test and matrix reasoning test assessed verbal knowledge and fluid reasoning, respectively. Participants also completed a perceptual similarities control task in which they rated the similarity of circles that had been created to vary on two dimensions: size and shading (Fig. 1c,d). This control task assessed whether developmental changes in emotion concept representation could be explained either by age-related developments in the general ability to represent two dimensions simultaneously or by low-level task behaviours such as extreme scale use.

Robust regressions revealed that all potential mediators increased with age: verbal knowledge (that is, raw vocabulary test scores), $\beta=0.68$, $P<0.001$; fluid reasoning (raw matrix reasoning test scores), $\beta=0.43$, $P<0.001$; shading focus (the weight placed on the second dimension in the perceptual similarities control task), $\beta=0.32$, $P<0.001$; and perceptual bidimensionality (the bidimensionality of participants' representations of non-emotional stimuli in the perceptual similarities control task), $\beta=0.27$, $P=0.004$. Arousal focus was significantly associated with verbal knowledge, $\beta=0.51$, $P<0.001$, fluid reasoning, $\beta=0.40$, $P<0.001$, and shading focus, $\beta=0.26$, $P=0.005$. Emotional bidimensionality was also significantly associated with verbal knowledge, $\beta=0.28$, $P=0.006$, fluid reasoning, $\beta=0.25$, $P=0.021$, and perceptual

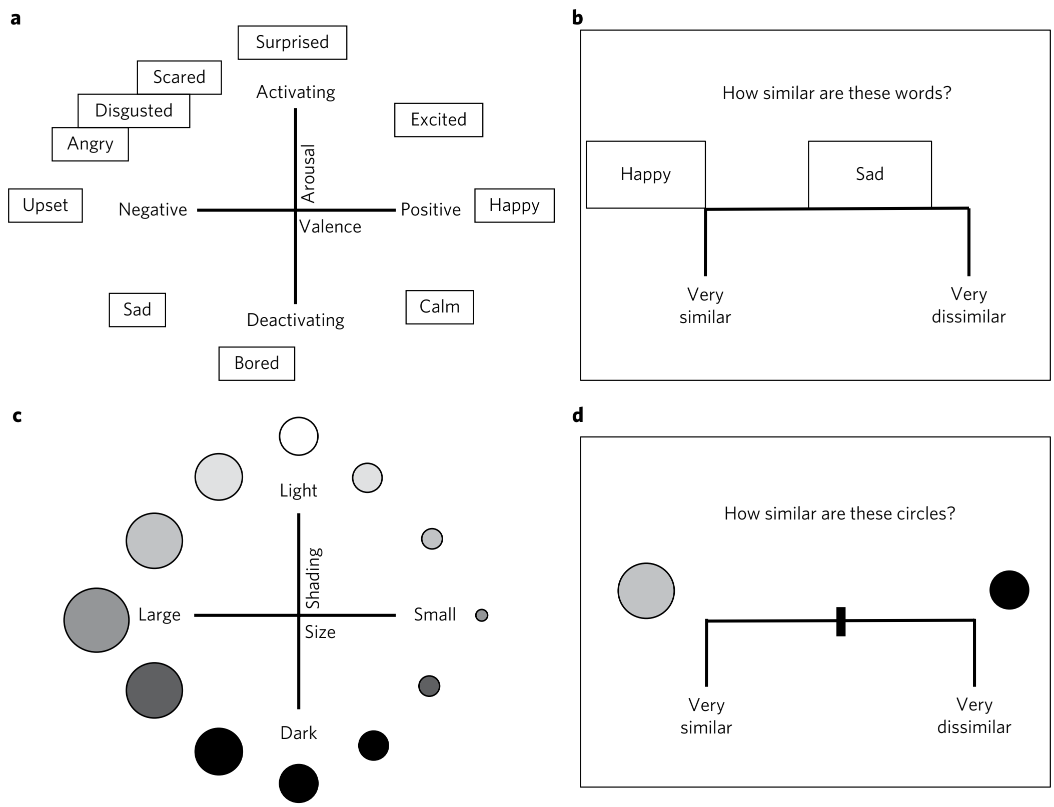

Fig. 1 | Schematics for the semantic similarities and perceptual similarities tasks. a, The ten emotion words used in the semantic similarities tasks, organized according to hypothesized positioning within the dimensions of valence (negative–positive) and arousal (deactivating–activating). **b**, Example trial from the semantic similarities task, in which participants rated the similarity of two emotion words by placing the word on the right closer to or farther away from the word on the left. **c**, Stimuli from the perceptual similarities task organized according to their constructed qualities, which varied along the dimensions of size (large–small) and shading (light–dark). **d**, Example trial from the perceptual similarities task, in which participants rated the similarity of two circles using a sliding scale.

bidimensionality, $\beta = 0.20$, $P = 0.024$. These results support the use of mediation analyses.

However, a robust bootstrapped mediation analysis revealed that only verbal knowledge significantly mediated the relationship between age and arousal focus (Fig. 4a). This analysis used a parallel mediation design to test whether verbal knowledge mediated age-related increases in arousal focus over and above the other potential mediators. Interestingly, no significant mediators emerged for the parallel mediation analysis of emotional bidimensionality. Verbal knowledge, indirect effect $\beta = 0.07$, 95% CI $= [-0.09, 0.22]$, 16.87% mediated, fluid reasoning, $\beta = 0.06$, 95% CI $= [-0.03, 0.26]$, 14.30% mediated, and perceptual bidimensionality, $\beta = 0.004$, 95% CI $= [-0.05, 0.07]$, 1.13% mediated, each failed to explain age-related changes in emotional bidimensionality.

However, a sequential mediation model revealed that increased verbal knowledge across age explained increased arousal focus, which in turn explained increased emotional bidimensionality (Fig. 4b). Hence, the development of emotional bidimensionality was explained by sequential increases in verbal knowledge and arousal focus with age. This sequential mediation had a fixed direction: sequential mediation was no longer significant when the order of verbal knowledge and arousal focus were reversed, $\beta = 0.005$, 95% CI $= [-0.02, 0.04]$, 1.81% mediated. Note that (1) these mediation models were no longer significant when including participants who demonstrated some—albeit incomplete—understanding of emotion terms (see Supplementary Note 2) and (2) these mediations did not hold for valence focus (see Supplementary Note 1). Hence, verbal knowledge mediated increased attention to the second emotion dimension (not reduced attention on the first dimension) only within people who had mastered the emotion terms used in the emotion concept tasks.

From our study using established tasks and a wide-ranging developmental sample, we conclude that emotion concept representations shift from a monodimensional, valence-focused representation to a bidimensional representation that emphasizes both valence and arousal. Mediation analyses reveal that increased arousal focus across age is explained by verbal knowledge but not fluid reasoning, the general ability to represent stimuli bidimensionally, or low-level task behaviours. Additionally, the sequential mediation analysis reveals that age-related increases in verbal knowledge explains increases in arousal focus, which in turn explains increased emotional bidimensionality.

Although robust evidence indicates that valence and arousal dimensions underlie how adults represent emotions[1,7–10], the present data show that this circumplex is not static across development. Emotion representations shift across age, eventually arriving at the bidimensional representation familiar to most psychologists. This gradual developmental shift has several theoretical implications. Because the constructionist theory of emotion posits that emotion concepts play a central role in both perceiving others' emotions and experiencing one's own emotions[1], if children lump emotion concepts within valences, this could influence their ability to make fine-grained distinctions between different emotion types. A valence-bound emotion conceptual repertoire may limit young children's emotional worlds to a 'positive versus negative' dichotomy. Indeed, research reviewed in the introduction suggests that

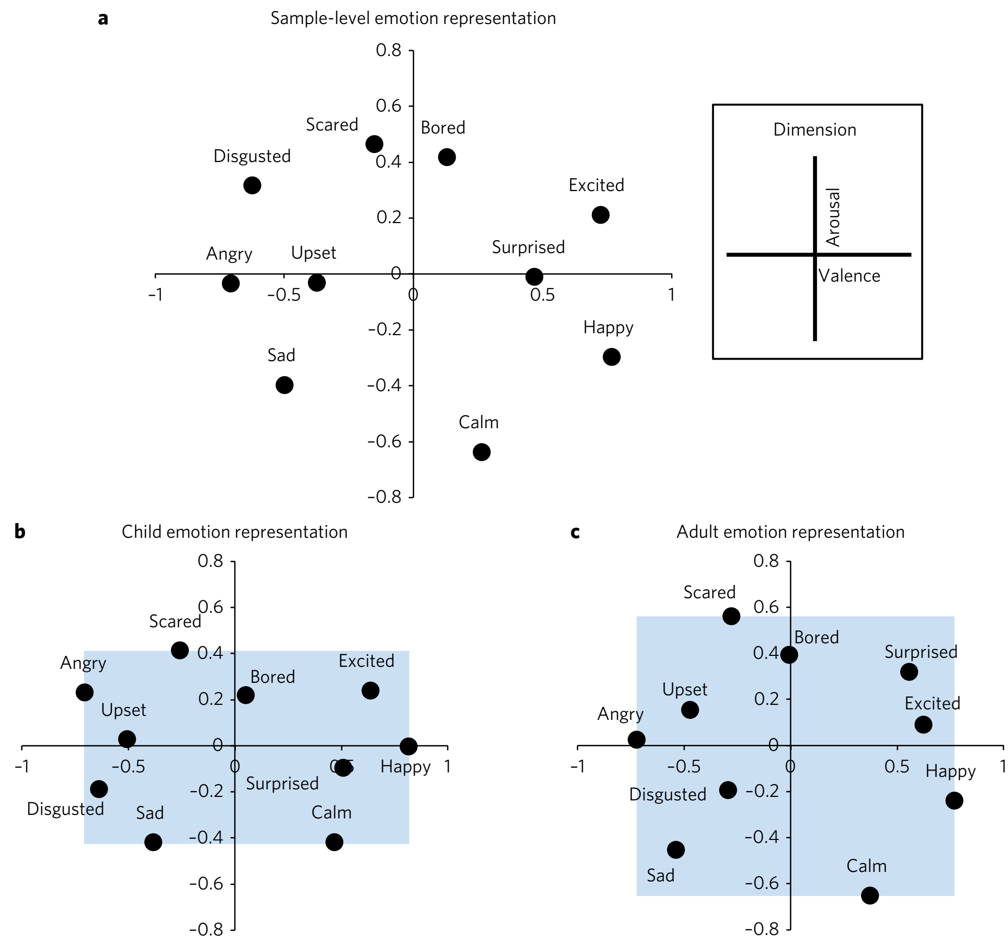

Fig. 2 | Visual depiction of sample-level emotion representation and changes in emotion representation across age. a, The overall sample-level emotion representation extracted from semantic similarities task ratings conformed to the circumplex model, as the first (horizontal) dimension represented valence (negative–positive), and the second (vertical) dimension represented arousal (activating–deactivating). **a**,**b**, Separate INDSCAL solutions of the ten youngest (**b**; $M_{age} = 8.04$) and the ten oldest (**c**; $M_{age} = 24.58$) participants revealed that children's emotion representations are wider (more spread along the valence dimension), shorter (less spread on the arousal dimension) and less bidimensional (more rectangular, rather than square) than adults' representations.

this is the case for both emotion perception and emotion experience. The present data extend this work by illustrating the development of emotion concepts themselves, providing a mechanistic explanation for dichotomized emotional experiences in childhood. Furthermore, assuming that emotion concepts are central components of emotions, our data demonstrate that even fundamental aspects (such as valence and arousal) change from childhood to adulthood. The long developmental course demonstrated here challenges theoretical views that aspects of emotion such as valence and arousal representations are fixed or universal.

In fact, our data indicate that emotion representations have a prolonged developmental trajectory. Because most studies on the development of emotion perception, emotion experience and emotion understanding are constrained to childhood, little is known about emotion conceptualization in adolescence. These results reveal that there are continued changes in emotion conceptualization throughout late adolescence and into early adulthood, a finding that prompts new questions about the role of emotion concept development in the social and affective changes that occur during adolescence[11]. Additionally, our methods ensured that all participants recognized emotion terms used in our tasks. This is a methodological advance on prior studies, which mostly assumed that child participants understood the terms used in tasks without systematically testing their comprehension. We believed that participants' responses on these tasks are only interpretable if we had evidence that they had a working understanding of each term, a decision that potentially augments the validity of these results. However, this methodological choice implies that merely having separate definitions for emotion words is not enough to produce a fully multidimensional emotion representation: The sophistication of emotion concepts continues to deepen even after people have learned to associate different emotion definitions with different emotion words.

The finding that verbal knowledge explained increased arousal focus and emotional bidimensionality across age converges with theoretical and empirical work on the role of language in shaping how people construct emotions[1–5], learn new conceptual distinctions[28,29] and understand the cognitive processes that underlie emotions[30–32]. A growing body of work indicates that linguistic labels 'feed back' to augment category learning and even influence perceptual experiences[28]. Our findings support this theory by demonstrating that verbal knowledge was the only variable to successfully explain increased multidimensionality of emotion representations across age. It is, however, crucial to note that general (that is, not emotional) verbal knowledge explained emotion concept development, because we ensured that all participants had equal emotional vocabulary. Two possible explanations for this pattern emerge. First, general developments in non-emotional vocabulary may

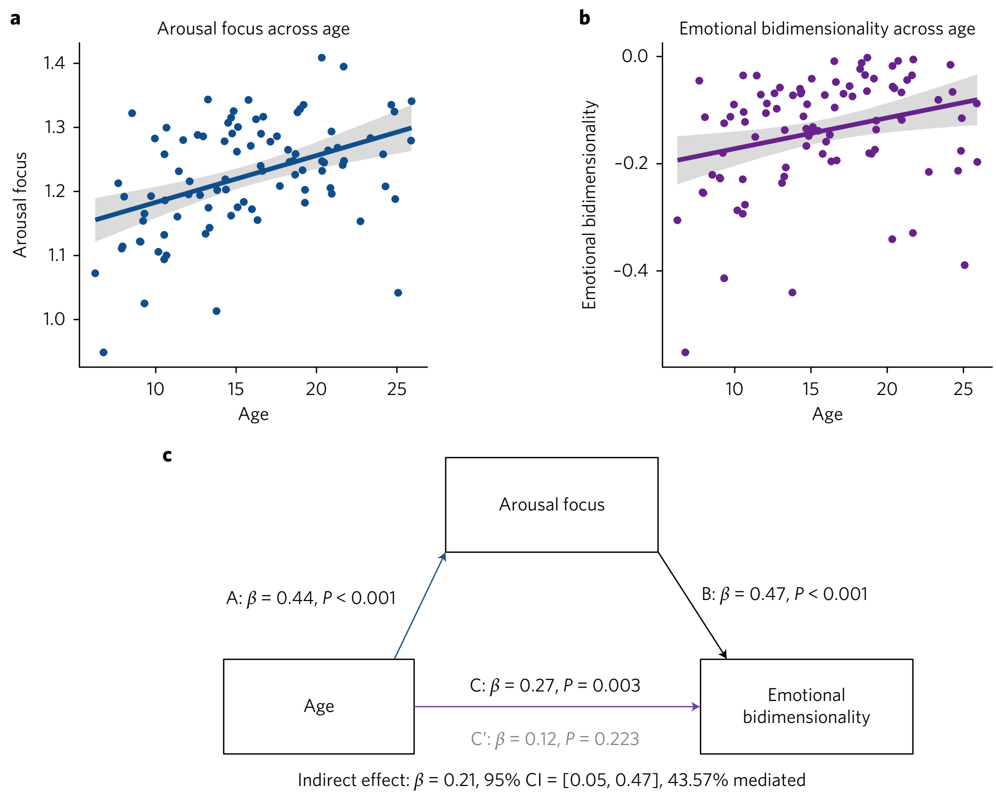

Fig. 3 | Changes in emotion representation across age. a,**b**, Both arousal focus (**a**) and emotion bidimensionality (**b**) increased across age. Lines of best fit and 95% confidence intervals (grey shading) were obtained from robust regression analyses. **c**, A robust bootstrapped mediation analysis suggested that increased emotional bidimensionality across age was explained by increased attention to differences in arousal between emotions. Colours illustrate relationships between age and arousal focus (blue) and age and emotional bidimensionality (purple) across panels. Capital letters denote statistics for mediation pathways.

play a 'bootstrapping' role in giving children the conceptual footholds needed to learn subtle distinctions between abstract emotion types[28,38]. Second, greater awareness of the multitude of emotion terms (that is, learning that English labels 'annoyance', 'frustration' and 'aggravation' as emotional states that are separate from 'anger') may expand concepts underlying emotion words already learned. These speculative explanations should be tested empirically.

Our data indicate that general intellectual development does not explain emotion concept development; developments in emotion concept representation were specifically associated with changes in verbal knowledge, not fluid reasoning[33]. Although we replicated prior work showing that the ability to produce non-emotional bidimensional representations increases across development[35], we did not find that this general skill explained bidimensional emotion representations. This dissociation merits further investigation: are emotion concepts truly 'special' in their developmental trajectory (that is, somehow divorced from this cognitive skill), or are there intervening mechanisms that complicate the connection between these two developmental trajectories? Although further data are needed to answer this question conclusively, it is theoretically parsimonious to posit that emotions scaffold on other developmental trajectories. We find that verbal knowledge provides one scaffold, but it is possible that another aspect of general cognitive development (beyond bidimensionality per se) also contributes to emotion concept development. Addressing this question presents a promising avenue of future developmental research that could address the origins and/or uniqueness of emotion knowledge.

A primary limitation of this study is its cross-sectional design. Without longitudinal data, we are limited in our ability to draw causal inferences about how the developmental trajectories of emotion concept understanding that we document relate to potential mechanisms within individuals. Similarly, although mediation models provide statistical support for the claim that verbal knowledge 'explains' multidimensional emotion representation, this technique is still correlational in nature. Future research should test for and rule out third variables that may underlie these effects.

The present study prompts several directions for future research. First, although valence-bound emotion conceptualization could provide a mechanistic explanation for dichotomized emotion perception and experience in childhood[1,14–19], this is an empirical question that could be directly addressed in future work. Second, given that having a specific grasp of one's own emotions is important for mental health, might inadequate dissociation of emotion concepts in early adolescence contribute to the increased emergence of mental health disorders at this period of life? The clinical implications of these findings deserve further attention[11,25]. Third, if multidimensional emotion concept representations are important to healthy development, are there interventions that could assist in this process? Studies demonstrate that educating both children and their parents about emotion can augment emotion understanding[39], so interventions (particularly those that augment verbal knowledge) may indeed boost this normative developmental process. Fourth, what factors speed or slow emotion concept development? Prior work shows that the presence of emotional and mental-state words in maternal speech aids the development of emotion understanding in children[32,40], so future researchers could assess whether household language also contributes to emotion concept development[26].

In all, the present study reveals that emotion representations are not static across life. Instead, moving from childhood to adulthood, people develop an understanding that emotions are more than

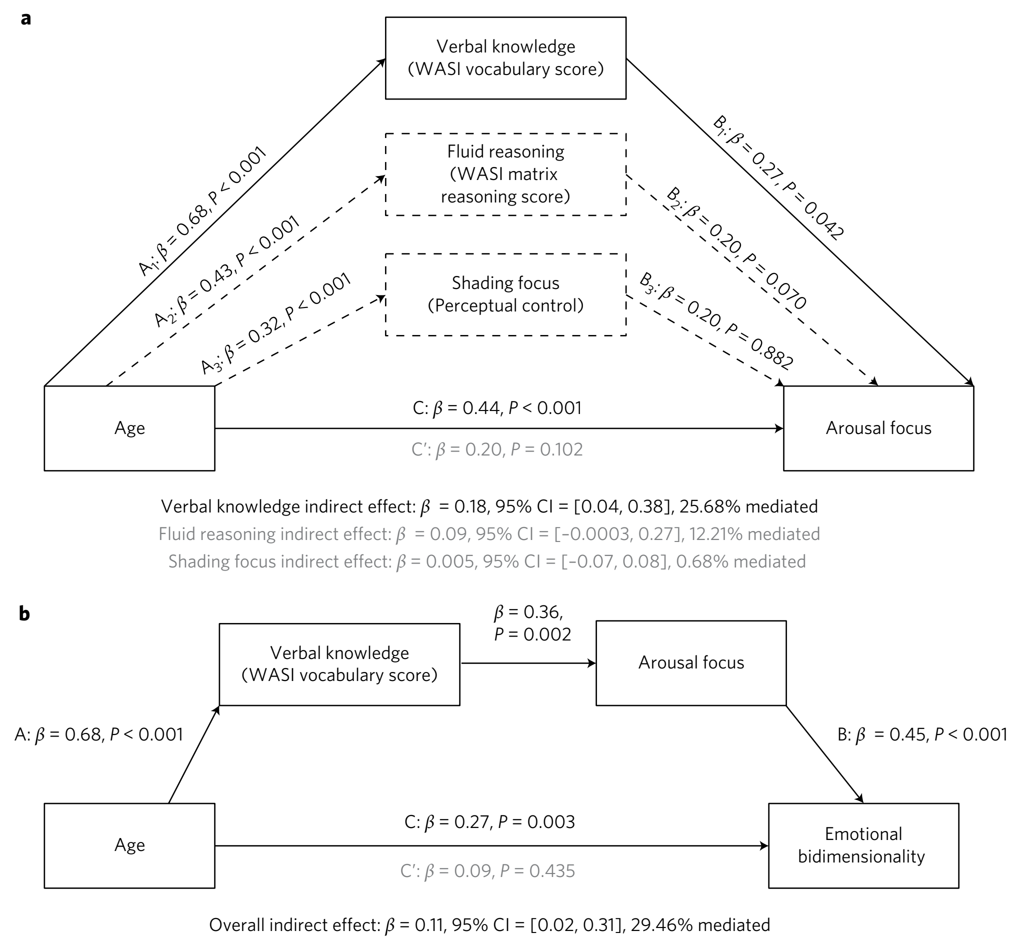

Fig. 4 | Results of robust bootstrapped mediation analyses examining potential mediators of emotion concept development. a, Verbal knowledge significantly mediated the relationship between age and arousal focus, over and above fluid reasoning and shading focus from the perceptual similarities control task. No other potential mediators were significant. **b**, The development of emotional bidimensionality could be explained by a sequential mediation: verbal knowledge increased with age, which led to increases in arousal focus, which in turn led to increased emotional bidimensionality. All mediation analyses used robust regressions, 10,000 resamples and BC_a confidence intervals.

just positive or negative and instead vary on multiple dimensions. The fact that this developmental trajectory scaffolds on general verbal knowledge supports emerging arguments on the role of language in emotion concept formation. These findings spur further directions of empirical study, lend mechanistic insight into theories of emotion development and may be integral to understanding the development of mood disorders.

Methods

Participants. Data reported in this manuscript were drawn from a large study on emotional development conducted by the authors. To provide a multifaceted view of how emotional processes develop, a large sample of people spanning ages 4 to 25 completed several tasks assessing emotional development. Decisions to analyse tasks presented in this manuscript were planned in advance to test hypotheses concerning emotion concept development. Additional components of the larger dataset have not yet been published.

Included participants ($N = 116$) were selected because they completed all of the measures used in this report. It was decided a priori that participants must understand the emotion words used in tasks. Hence, 24 participants were excluded because the emotion vocabulary assessment revealed that they did not demonstrate full understanding of emotion terms used in subsequent tasks, leaving 92 participants for primary analyses (age range = 6.24–25.91, mean $M_{age} = 15.76$, standard deviation $SD_{age} = 5.07$, 51.09% female, 54.35% Caucasian, two did not disclose race). We also present analyses including 17 participants who showed marginal understanding of emotion terms in Supplementary Note 1.

We did not include participants under the age of 6 in analyses for this report because the WASI-II[41] is not valid below 6 years of age. All participants were native English speakers who were compensated for their time and recruited from communities surrounding Harvard University and the University of Washington. Participants provided informed written consent/assent, and minor participants received written permission for their participation from a parent or legal guardian. The Committee on the Use of Human Subjects at Harvard University and the University of Washington Institutional Review Board approved all research procedures. Because no prior work has investigated emotion concept development across such a wide age range, a priori power analysis was not possible. However, a post-hoc power analysis confirmed that we had sufficient (83.23%) power to detect medium effect sizes ($\beta = 0.30$) with 92 participants.

Study overview. This study comprised an emotion vocabulary test used as a screening tool for emotion word comprehension, the semantic similarities task which served as the primary dependent measure of emotion concept representations, a less structured word-sort task to serve as an ancillary measure of emotion concept development, the vocabulary and matrix reasoning subscales of the WASI-II[41] to assess verbal knowledge and fluid reasoning, and a control task to evaluate bidimensional perceptual representation. Participants completed the emotion vocabulary assessment, word-sort task and semantic similarities task in the laboratory. They completed the other measures in a follow-up experimental session that was administered over the internet under the guidance of an experimenter available by phone.

Emotion vocabulary test. We adapted previous methods[27] to assess participants' understanding of 27 emotion terms (that is, amazed, angry, annoyed, bored, calm, disappointed, disgusted, embarrassed, excited, grumpy, happy, hate, jealous, lonely, love, nervous, pleased, proud, relaxed, sad, safe, scared, sorry, surprised, thankful, upset and worried). These emotions were selected to include (1) basic emotions[42], (2) emotions that correspond to all four quadrants of the circumplex dimensions of valence and arousal[7] and (3) a mix of emotions that young children can identify (for example, angry, happy, sad) as well as some that emerge later in development (for example, disappointed)[27]. The experimenter said an emotion word out loud, showed the participant a card with that emotion word written on it, and asked the participant to do their best to say what that word meant. Responses were audio-recorded.

Similar to a WASI vocabulary test, trained experimenters assigned each definition a score of 0, 1 or 2. A score of 2 was awarded if the response included (1) a plausible abstract definition of the emotion, (2) a synonym of the emotion or (3) a situation that would conceivably evoke the given emotion and not other emotions. We assembled a list of definitions and synonyms for each emotion from commonsense, dictionary and thesaurus sources which experimenters could refer to during the session (see Supplementary Note 3). If the participant did not provide a response that merited a score of 2, the experimenter prompted them to give more information to ensure that impoverished responses were not due to test anxiety or shyness. If, even after prompting, participants only gave definitions/situations that were of the correct valence but too vague to meet criteria for a two-point response, that definition received a score of 1. If participants responded saying "I don't know" or gave definitions, synonyms or situations for emotions of a different valence, that definition received a score of 0. This test allowed us to verify that participants understood emotion words used in other tasks. We excluded participants who did not fully understand one or more of the ten emotion words used in the semantic similarities task from primary analyses, but we present analyses that relax this criterion to include participants who demonstrated partial comprehension of these emotion words (that is, they received at least 1 point for each word) in Supplementary Note 2 and Supplementary Fig. 1.

Semantic similarities task. The semantic similarities task provided a fine-grained assessment of emotion concept representation and constituted our primary dependent variable[9,37]. In this task, participants indicated how similarly they perceived two emotion words to be using a sliding scale (Fig. 1a,b). For each trial, one word was fixed on the left side of the screen, and participants used the mouse to move the other word along a scale that ranged from 'very similar' to 'very dissimilar.' Placing the words closer together indicated that participants thought the emotions were more similar to each other, and placing them farther apart indicated that they thought the emotions were less similar. Participants rated all possible pairs of ten emotion words (that is, angry, bored, calm, disgusted, excited, happy, sad, scared, surprised and worried). This set includes emotions that are typically understood by young children and represent all four quadrants of the circumplex[7,27]. Ratings were self-paced. Trial order and assignment of words to left or right positions were randomized across participants.

We recorded participants' similarity ratings (expressed as a percentage of the scale) and organized these ratings into dissimilarity matrices. Conceptually, each participant's dissimilarity matrix captured the 'semantic distance' separating each of the ten emotions within that participant's representation of emotion, based on their ratings. We then applied multidimensional scaling (MDS) analyses—specifically, the individual differences multidimensional scaling procedure (INDSCAL)[43]—to these dissimilarity matrices, following prior work[9,20]. We used the *indscal* function in the *smacof* R package[44]. This analysis used both participant-level and sample-level information in the dissimilarity matrices to (1) reveal underlying dimensions of participants' emotion groupings and (2) compute the relative weight that participants placed on each of these dimensions when sorting emotions. Given robust work demonstrating that valence and arousal are two primary dimensions underlying emotion representation[7,9], we fitted a two-dimensional interval INDSCAL model (stress = 0.26)[45].

The INDSCAL model produced four measures of interest: (1) sample-level representations of emotions along the two primary dimensions underlying participants' ratings, (2) valence focus (the 'weight' or salience each participant placed on the first dimension while rating emotions) (3) arousal focus (the 'weight' that each participant placed on the second dimension) and (4) emotional bidimensionality (the extent to which each participant's emotion representation was balanced along both dimensions). We first extracted the overall sample-level representation of emotions along each dimension from the INDSCAL model to verify that the first two dimensions underlying participants' ratings in this task represented valence and arousal. We then extracted the 'weight' that each participant placed on each dimension while rating emotions. Greater weight indicates a greater relative saliency of that dimension over the other dimension while rating emotions. We called these weights valence focus and arousal focus. Finally, we computed the bidimensionality of each participant's emotion representation. Using group-normalized configurations within the INDSCAL model (which ensured that the two axes represented valence and arousal for all participants), we computed the width of each participant's emotion representation along each axis (that is, valence width = [x-coordinate of most positive emotion] – [x-coordinate of most negative emotion]). We produced emotional bidimensionality scores by subtracting each participant's larger width from their smaller width. This ensured that more negative scores indicated more 'unbalanced' (that is, rectangular) emotion representations, and a score of 0 represented perfect bidimensional balance (that is, a square representation).

Word-sort task. In the word-sort task,[20,46] participants were given the emotion cards for which they had received a score of 1 or 2 on the emotion vocabulary assessment and asked to freely sort them into piles depending on 'which emotions belong together'. This task provided a more unstructured depiction of how participants grouped emotions and was also analysed using MDS methods. Although the sample-level emotion representation in this task replicated the semantic similarities task, analyses of valence focus, arousal focus and bidimensionality from this task did not (see Supplementary Note 4 and Supplementary Figs. 2 and 3). We report these data for full scientific transparency and discuss the divergence between these tasks in the Supplementary Information.

Verbal knowledge and fluid reasoning assessment. We assessed verbal knowledge using the vocabulary subtest of the WASI-II[41]. Participants defined a series of words, and trained assessors gave scores of 0, 1 or 2 for each answer following the WASI manual. Scores were summed to form our measure of verbal knowledge. We assessed fluid reasoning using the WASI matrix reasoning subtest. Participants saw a series of shapes that followed a logical pattern and had to select a shape that best completed the pattern. Answers were scored as 0 or 1 (incorrect or correct). As in prior research[47], scores were summed to form a measure of fluid reasoning. To verify that our sample did not suffer from cohort-related differences in intelligence across ages, we also used the WASI manual to transform raw sums of scores into age-normed (1) T-scores for verbal intelligence, (2) T-scores for fluid reasoning intelligence and (3) full-scale IQ.

Perceptual similarities task. We designed a control task for the semantic similarities task to assess participants' ability to represent non-emotional stimuli on two dimensions. Participants rated the perceptual similarities between 12 circles that varied on two dimensions (size and shading; Fig. 1c,d). We subjected dissimilarity ratings in this task to an interval INDSCAL model (model stress = 0.26) and extracted (1) sample-level representations of the circles along the two primary dimensions, (2) participant-level weights for each of the resulting dimensions (called size focus and shading focus) and (3) perceptual bidimensionality scores (again, by subtracting the larger 'width' from the smaller 'width' of each participant's individual perceptual representation). Note that one circle was excluded to recover the bidimensional representation inscribed in the stimuli (see Supplementary Note 5 and Supplementary Fig. 4).

Developmental shifts in emotion representations. We used robust regression analyses to test for linear changes in valence focus, arousal focus, and emotional bidimensionality across age. All regression analyses were robust using the *rlm* function in the *MASS* package[48] to ensure they were not biased by single, highly influential data points. Valence focus and arousal focus were strongly negatively correlated, $r(90) = -0.96$, $P < 0.001$. Hence, we focused our report on analyses of arousal focus and emotional bidimensionality and report analyses of valence focus in Supplementary Note 1. We examined whether increased emotional bidimensionality across age could be explained by development in arousal focus. We conducted a robust bootstrap mediation analysis with 10,000 resamples using *rlm* regressions and the *boot* package[49] to examine whether arousal focus mediated the relationship between age and emotional bidimensionality. Significant mediation at an α level of 0.05 was defined as 95% bias-corrected and accelerated (BC_a) confidence intervals (CIs) of the indirect effect that did not include 0. We also report proportion mediated (as % mediated) as a measure of effect size. All tests were two-sided.

Potential mediating mechanisms. We investigated four potential mechanisms that might explain developmental changes in emotion representation using robust mediation analyses: (1) verbal knowledge, (2) fluid reasoning, (3) changes in general abilities to represent two dimensions and (4) changes in low-level task behaviours (for example, the tendency to choose the ends of the scale). These were operationalized via the following four variables: (1) unscaled WASI-II vocabulary test scores, (2) unscaled WASI-II matrix reasoning test scores, and (3 and 4) size focus and perceptual bidimensionality from the perceptual similarities control task.

For each potential mediator, we first conducted robust regressions to assess whether they (1) varied across age, (2) were significantly related to arousal focus and (3) were significantly related to emotional bidimensionality. We then conducted four robust bootstrap mediation analyses with 10,000 resamples each. The first tested whether any or all of these mediators explained age-related changes in arousal focus. Verbal knowledge scores, fluid reasoning scores and size focus were modelled as parallel mediators of the relationship between age and arousal focus (Fig. 4a). This analysis tested whether any potential mediator was significant even after controlling for all other potential mediators. We conducted a second robust mediation analysis to test whether the three parallel mediators of verbal knowledge scores, fluid reasoning scores and/or perceptual bidimensionality mediated changes in emotional bidimensionality across age. Note that we focus on whether shading focus mediated age-related changes in arousal focus to assess whether developmental changes in the ability to detect the 'non-dominant' (or secondary) perceptual dimension was related to developmental changes in arousal focus (that is, the ability to detect the 'non-dominant' or secondary emotion dimension). Likewise, we assessed whether perceptual bidimensionality mediated the development of emotional bidimensionality. These appeared to be the best a priori parallel control analyses to assess whether general abilities in two-dimensional perception and/or low-level task behaviours in the perceptual control task explained age-related changes in emotion representation metrics.

Because we found that only verbal knowledge mediated increased emotional bidimensionality across age, the third mediation analysis was a sequential mediation model testing whether increased verbal knowledge produced increased emotional bidimensionality across age through increased arousal focus (Fig. 4b). The fourth and final mediation analysis tested the directional specificity of this sequential mediation model by reversing the order of verbal knowledge and arousal focus. Potential mediators were only moderately correlated, $r=0.36$–0.54. Based on prior work, we hypothesized that verbal knowledge, fluid reasoning, size focus and perceptual bidimensionality would all increase with age, but that verbal knowledge would be the strongest mediator of age-related changes in arousal focus and emotional bidimensionality[28,30,35,50].

Ruling out possible intelligence confound. We ensured that our sample did not suffer from cohort-related intelligence confounds by conducting robust regressions testing whether age was significantly related to age-normed verbal intelligence T-scores, fluid reasoning T-scores or full scale IQ. No significant relations emerged between age and full-scale IQ ($\beta=-0.02$, $P=0.852$), age-normed verbal knowledge T-scores ($\beta=0.06$, $P=0.578$) or age-normed fluid reasoning T-scores ($\beta=-0.08$, $P=0.505$). Hence, our sample does not suffer from cohort-related IQ confounds, indicating that age-related variations in emotion concept representation cannot be explained by biased sampling. Results of these control analyses are identical when including participants who demonstrated some—although incomplete—knowledge of emotion terms (see Supplementary Note 2).

Life Sciences Reporting Summary. Further information on experimental design is available in the Life Sciences Reporting Summary.

Data availability. Data for this report are available through the Open Science Framework repository[51], https://osf.io/xe4ps/.

Code availability. Code used to produce analyses and figures in this report is available through the Open Science Framework repository[51], https://osf.io/xe4ps/.

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Author contributions

Authors collaboratively developed the study design. E.C.N. programmed computer tasks. E.C.N., S.F.S. and H.K.L. collected data. E.C.N. analysed data. E.C.N. and L.H.S. interpreted results. E.C.N. drafted the manuscript, and all other authors provided critical revisions. All authors approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

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Experimental design

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Describe how sample size was determined.	Data reported in this manuscript were drawn from a larger study on emotional development. Included participants (N=116) were selected because they completed all of the measures used in this report. It was decided a priori that participants must understand the emotion words used in tasks. Hence, 24 participants were excluded because the emotion vocabulary assessment revealed that they did not demonstrate full understanding of emotion terms used in subsequent tasks, leaving 92 participants for primary analyses. We did not include participants under the age of 6 because the Wechsler Abbreviated Scale of Intelligence (WASI-II) is not valid below 6 years of age. Because no prior work has investigated emotion concept development across such a wide age range, an a priori power analysis was not possible. However, a post-hoc power analysis confirmed that we had sufficient (83.23%) power to detect medium effect sizes (β =.30) with 92 participants.

2. Data exclusions

Describe any data exclusions.	See 1.

3. Replication

Describe whether the experimental findings were reliably reproduced.	No replication was attempted.

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Describe the software used to analyze the data in this study.	The boot and rlm functions in R. All packages are cited in the manuscript.

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