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Interoception: the forgotten modality in perceptual grounding of abstract and concrete concepts

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Conceptual representations are perceptually grounded, but when investigating which perceptual modalities are involved, researchers have typically restricted their consideration to vision, touch, hearing, taste and smell. However, there is another major modality of perceptual information that is distinct from these traditional five senses; that is, interoception, or sensations inside the body. In this paper, we use megastudy data (modality-specific ratings of perceptual strength for over 32 000 words) to explore how interoceptive information contributes to the perceptual grounding of abstract and concrete concepts. We report how interoceptive strength captures a distinct form of perceptual experience across the abstract–concrete spectrum, but is markedly more important to abstract concepts (e.g. *hungry*, *serenity*) than to concrete concepts (e.g. *capacity*, *rainy*). In particular, interoception dominates emotion concepts, especially negative emotions relating to *fear* and *sadness*, moreso than other concepts of equivalent abstractness and valence. Finally, we examine whether interoceptive strength represents valuable information in conceptual content by investigating its role in concreteness effects in word recognition, and find that it enhances semantic facilitation over and above the traditional five sensory modalities. Overall, these findings suggest that interoception has comparable status to other modalities in contributing to the perceptual grounding of abstract and concrete concepts.

This article is part of the theme issue 'Varieties of abstract concepts: development, use and representation in the brain'.

1. Introduction

Concepts are the basis of the human cognitive system, and the question of what constitutes the content of these mental representations has long occupied the cognitive sciences. Work in recent decades has converged on the idea that we develop our conceptual representations through our perception of and interaction with our environment (e.g. [1–3]). That is, the conceptual system has co-opted the perceptual system for the purposes of representation. To date, such research has typically restricted consideration to the perceptual modalities of vision, touch, hearing, and, to a lesser extent, taste and smell (e.g. [4–6]). However, there is another major modality of perceptual information that is distinct from these traditional five senses; that is, interoception, or sensations within the body.

Interoception is a broad term that refers to perception internal to the body's surface, and incorporates sensations from the visceral organs (e.g. heart, lungs, stomach) along with autonomic, hormonal and even immunological signals [7–10]. Sensations classed as interoception include cardiovascular, respiratory, gastrointestinal, bladder, hunger, thirst, blood/serum (pH, osmolality, glucose level), temperature, vasomotor flush (i.e. hot flushes), air hunger (i.e. breathlessness), muscle tension, shudder, itch, tickle, pleasure, genital sensation and sensual touch; as well as painful sensations such as inflammation, bone fracture or headache. The common role of these sensations is to help maintain physiological homeostasis (i.e. the stable and efficient functioning of the body's dynamically interdependent parts). In addition, because emotional experience incorporates physiological and visceral changes, there has also been some speculation regarding how interoceptive sensations contribute to the processing of emotions (e.g. [7,9,11,12]).

With such an expansive list of associated sensations, it may seem that interoception is quite different from other perceptual modalities, but this is not necessarily the case. A broad range of sensations also exists within other modalities, such as vision (incorporating colour, pattern, movement, shape, spatial distance, etc.) and touch (incorporating pressure, texture, movement, vibration, tactile cold/heat, etc.). The breadth of interoception does not mean that it cannot be considered as a coherent perceptual modality; rather, compared to the five classic modalities, we suggest that people are not generally accustomed to thinking of interoception as a single category of experience. The various aspects of interoceptive sensation can also be measured using similar methods to studies of sensory perception in the other modalities, such as attention (passive or active), detection, magnitude/intensity judgements, discrimination, accuracy/sensitivity and qualitative self-report approaches [10]. For instance, while people are not always aware of interoceptive sensations from internal organs such as the heart, it is possible to attend consciously to these sensations and, indeed, heartbeat detection [13] or counting [14] is a classic task in the empirical investigation of interoceptive perception. In other words, like the traditional five modalities of vision, touch, hearing, taste and smell, interoception is a physiologically distinct category of perceptual experience.

Current neural models describe interoception as a construct of the central nervous system, reflecting communication between the periphery (i.e. the body) and the brain in the maintenance of homeostasis [7,9,13]. For example, one influential view [7,8] describes interoception as following an ascending pathway, starting at the receptor site, from where information is relayed via spinal or cranial nerves to the brainstem, sub-cortical structures (e.g. thalamic nuclei, hypothalamus, amygdala) and ultimately to the cortex, in particular the insula and cingulate cortex (ACC), but also the inferior and medial frontal cortex, somatosensory and somatomotor cortex (see also [13]). Within this framework, a posterior-to-anterior progression of increasing representational complexity in the insula acts to integrate information from different homeostatic pathways, sensory signals from the secondary somatosensory cortex, as well as information from the amygdala, hypothalamus, emotional activity in the ACC and orbitofrontal cortex and 'contextual planning' area of the dorsolateral prefrontal cortex. Thus, current neural models for interoception suggest that the insula is the critical cortical region for the formation of an integrated interoceptive representation. Indeed, neuroimaging and lesion studies have shown that the dorsal posterior insula is active in pain, temperature, itch, dynamic or painful muscle sensation, sensual touch, hunger, thirst, gustation, cardiorespiratory activity and air hunger (see [7] for a review), these sensations all falling within the broad definition of interoception. As such, like the traditional five modalities of vision, touch, hearing, taste and smell, interoception is a cortically distinct category of perceptual experience.

2. Perceptual grounding of concepts

Modality-specific perceptual experience is important to how concepts are grounded. For example, when reading the word *cinnamon*, olfactory processing areas of the brain also become activated even though there is no cinnamon scent present [15]. That is, the concept of *cinnamon* is perceptually grounded in the systems that process olfactory experience because representing the meaning of the word *cinnamon* involves reactivating of some of the neural areas involved in perceptual experience of its referent. Many behavioural studies also highlight the importance of information from all five basic modalities in predicting performance across a range of conceptual tasks, including modality-switching cost paradigms [5,16], word modality detection/categorisation [17], conceptual combination [18], attentional blink [19], recognition memory [20] and word recognition [21–24]. For instance, the strength of perceptual experience in the auditory modality is a reliable predictor of word naming times (i.e. reading aloud), a word recognition task where auditory monitoring of the speech stream ensures correct word production, but it does not predict lexical decision times, which is a word recognition task that uses *silent* reading [22].

While the majority of the above empirical work has concentrated on concrete concepts, there is evidence that individual modalities of perceptual experience are important to abstract concepts as well. Many words that are traditionally considered to be abstract, and, therefore, score low on concreteness and imageability ratings, nonetheless score highly on individual modalities of perceptual strength [21]. For example, despite being rated as abstract, *fear* is strongly visual, *noisy* is strongly auditory and *quality* is strongly multimodal across all five modalities of touch, taste, smell, sound and vision. Perceptual strength in the dominant modality is an important predictor of how easily words are recognized across the abstract–concrete spectrum [22,23,25], better than concreteness or imageability ratings [21]. That is, concepts such as *fear* or *noisy* are grounded in the perceptual modalities through which they are experienced, and the extent of experience in a particular modality can be used to successfully predict conceptual processing in a range of cognitive tasks. The evidence to date, therefore, demonstrates that concepts rely on the five traditional perceptual modalities to provide a grounded basis to their representation, but it remains unknown to what extent grounding may also rely on interoceptive information.

Our goal in the present paper was to explore how interoception contributes to the perceptual grounding of concepts. Using a megastudy dataset of perceptual strength ratings in six modalities (auditory, gustatory, haptic, olfactory, visual and interoceptive) for over 32 000 concepts [26], we ran a series of exploratory analyses to examine whether and how interoception plays a major role in experience of both abstract and concrete concepts. In particular, since interoception has been linked to emotional experience, we explored whether interoceptive strength plays an especially large role in the experience of emotions such as *happiness*, *fear* and *love*. Finally, we examined whether interoceptive strength contributes to perceptual grounding by assessing its role in semantic facilitation of word recognition.

3. Study 1: interoception in abstract and concrete concepts

Since all concepts are perceptual to some extent, even traditionally abstract ones like *republic* and *theory* [21,27], it is plausible that interoception may be important to both abstract and

Table 1. Number and percentage of concepts according to their dominant perceptual modality, both overall and within abstract and concrete subsets.

	auditory		gustatory		haptic		interoceptive		olfactory		visual	
category	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%
abstract	2945	17.2	96	0.6	183	1.1	2322	13.6	46	0.3	11 537	67.4
concrete	893	5.9	655	4.3	637	4.2	459	3.0	128	0.8	12 328	81.6
overall	3838	11.9	751	2.3	820	2.5	2781	8.6	174	0.5	23 865	74.0

concrete concepts. In our first study, we aimed to establish the extent to which interoception plays a role in how people experience concepts across the abstract–concrete continuum.

(a) Method

(i) Materials

A total of 32 229 concepts were compiled for which perceptual strength norms existed on six individual perceptual modalities: hearing, taste, touch, interoception, smell and vision. Most concepts were labelled with a single word ($N = 29\,887$) but some concepts such as *heart attack* were labelled with a two-word lexicalized phrase ($N = 2342$). These words represented the total sample of completed items available at the time of analysis from a norming megastudy [26] that aimed to collect ratings of perceptual and action strength for all English words that are known by 85% of native speakers (i.e. some 40 000 words [28]). In these norms, participants were asked to rate 'to what extent do you experience WORD' through each of six sensory modalities (i.e. 'by hearing', 'by tasting', 'by feeling through touch', 'by sensations inside the body', 'by smelling' and 'by seeing'), using separate rating scales for each modality ranging from 0 (not at all) to 5 (greatly). Inter-rater agreement was excellent for each modality (Cronbach's αs greater than 0.9). This norming method had previously been used to establish modality-specific experiential strength in the traditional five modalities (i.e. excluding interoception) for comparatively modest samples of several hundred words [5,24,27], where the resulting norms successfully predicted a range of findings in word recognition [21–23,25] and conceptual processing [5,17]. Perceptual strength norms, therefore, comprised a six-value vector per word of auditory, gustatory, haptic, interoceptive, olfactory and visual strength, each ranging from 0 (low strength) to 5 (high strength).

(ii) Design and analysis

Data were analysed with two exploratory goals in mind: to determine the importance of interoceptive strength relative to other perceptual modalities and across conceptual domains, and to examine whether and how interoceptive strength and dominance differed between abstract and concrete concepts. Since these analyses were exploratory rather than confirmatory, we report no inferential statistics. All datasets and code for Studies 1–3 are available [29].

We categorized concepts as abstract or concrete using concreteness ratings on a five-point scale [28], where abstract concepts were those rated between 1.00 and 2.99 ($N = 17\,129$) and concrete concepts were those rated between 3.00 and 5.00 ($N = 15\,100$). For more in-depth comparisons within degrees of concreteness, we further split these categories into very abstract (1.00–1.99), somewhat abstract (2.00–2.99), somewhat concrete (3.00–3.99) and very concrete (4.00–5.00). Following previous conventions for categorizing concepts by perceptual strength [5], we also split by interoceptive strength into categories of weak (rating range 0.00–1.49), moderate (1.50–3.49) and strong (3.50–5.00)

(b) Results and discussion

(i) Importance of interoceptive information

Inter-correlations of perceptual strength ratings show that interoceptive experience was relatively distinct from other modalities. It was negatively related to visual ($r = -0.325$) and haptic ($r = -0.078$) strength, and positively related to auditory ($r = 0.142$), gustatory ($r = .095$) and olfactory ($r = 0.042$) strength. In other words, that which can be sensed inside the body tends not to be visible or touchable, but can sometimes be heard, tasted or smelled to some extent, although none of the relationships were particularly strong. In order to quantify the distinctness of interoceptive information, we ran principal components analysis across all six modalities and examined how the extracted components incorporated each original variable. Parallel analysis (i.e. Monte Carlo simulation of the 95th percentile of eigenvalues) determined that the optimal number of components to extract was two, explaining 58.9% of the original variance, and these components were then orthogonalized via varimax rotation. Uniqueness scores (i.e. the proportion of variance from each variable that is not shared with the extracted components) showed that a little more than half of the information in interoceptive strength ratings was unique (52.2%), less than that of auditory strength (74.1%), but more than gustatory (19.1%), haptic (43.1%), olfactory (21.1%) or visual (36.8%) strength.

Interoception dominated a sizeable number of concepts (i.e. interoceptive strength was the highest rating of all six modalities), some 8.6% in total. In terms of relative importance, interoception dominated more concepts than taste, smell and touch combined, but fewer than hearing or vision (table 1); the pattern of dominance across the five traditional modalities was consistent with previous findings [5,15]. Many interoceptively dominant concepts related to the domains of sensation that are typically associated with interoception in the perceptual and neuroimaging literature, including cardiovascular (e.g. *heart*, *heartbeat*, *bloodstream*), pulmonary (e.g. *breathing*, *asphyxiation*, *inhale*), gastrointestinal (e.g. *hunger*, *thirst*, *nausea*), thermoregulatory (e.g. *cool down*, *warmness*, *heatwave*), genitourinary (e.g. *orgasm*, *urination*, *ejaculate*) and pain (e.g. *painful*, *agony*, *bellyache*) systems. Other notable domains that were dominated by interoceptive perception included fatigue (e.g. *tired*, *sleepy*, *wearily*), pregnancy (e.g. *fetus*, *contraction*, *gestational*), illness and injury (e.g. *diabetes*, *influenza*, *whiplash*), drugs (e.,g. *caffeine*, *heroin*, *amphetamine*) and a wide variety of

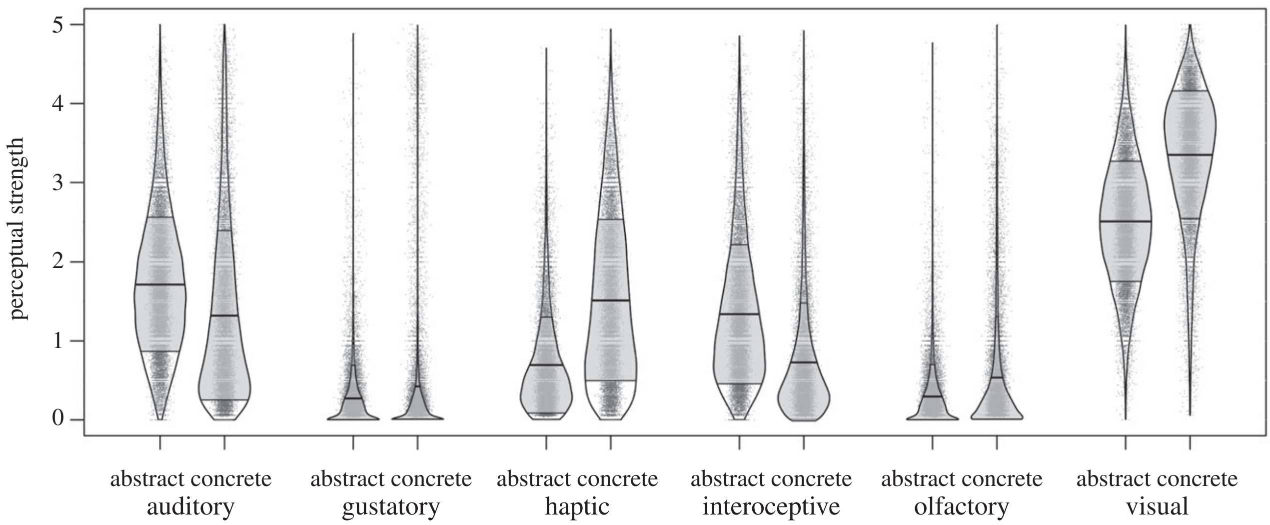

Figure 1. Distribution of modality-specific perceptual strength ratings for abstract and concrete concepts. Shaded areas represent one standard deviation each side of a central mean line.

emotion concepts (e.g. *anger*, *sadness*, *fear*, *joy*, *happy*). Without interoceptive strength, many of these interoceptively dominant concepts would have been regarded as perceptually weak (i.e. when only the five traditional perceptual modalities were being considered). For instance, *adrenaline*, *jetlag* and *anxiously* were strongly interoceptive (strength ratings greater than 4) but were very weak in all other modalities (ratings less than 1).

Overall, this pattern of findings suggests that interoceptive strength ratings capture distinctive information about perceptual experience that is not represented in the traditional five sensory modalities. Moreover, this distinctive interoceptive information offers a potential means of grounding a wide variety of concept types that would otherwise have been misinterpreted as lacking perceptual information.

(ii) Interoception in abstract and concrete concepts

Across a number of related measures, interoception was more strongly associated with abstract concepts than concrete concepts. Interoceptive strength was negatively correlated with concreteness ratings ($r = -0.397$): that is, concepts that were strongly experienced via sensations inside the body tended to be regarded as abstract rather than concrete. As previously observed [21], concreteness was also negatively correlated with auditory strength ($r = -0.223$), and positively with visual ($r = 0.562$), haptic ($r = 0.526$), gustatory ($r = 0.159$) and olfactory ($r = 0.257$) strength. Most notably, the magnitude of the relationship between interoception and concreteness was in the middle of the range, less than that of sight and touch, but greater than that of sound, taste and smell.

Since concepts are commonly split dichotomously into abstract and concrete categories, typically at the midpoint of the concreteness scale, we examined interoceptive strength from this perspective. As shown in figure 1, interoceptive strength ratings were markedly higher for abstract concepts ($M = 1.34$, s.d. $= 0.89$) than for concrete concepts ($M = 0.73$, s.d. $= 0.75$). All other modalities, with the exception of audition, followed the opposite direction whereby perceptual strength ratings were higher for concrete concepts than abstract. However, it was possible that this apparent negative relationship between interoception and concreteness was an artefact of the particular concepts near the midpoint of the concreteness scale, where ratings tend to be noisier than ratings at the extremes because they often reflect participant disagreement or confusion [30]. If this were the case, then unequivocally abstract concepts (i.e. those close to the extremely abstract end of the scale) may actually be experienced only weakly via interoception, whereas unequivocally concrete concepts may be interoceptively strong. To explore this possibility, we used a more fine-grained breakdown of concreteness ratings into four categories from very abstract to very concrete, and examined concepts in three categories of interoceptive strength: weak, moderate and strong (table 2). Strongly interoceptive concepts occurred across the full range of the abstract–concrete scale and were nearly three times more numerous at the very abstract extreme ($N = 146$) than at the very concrete extreme ($N = 46$), while concepts with moderate interoceptive strength followed a similar but more pronounced pattern. Conversely, interoceptively weak concepts were more numerous at the extremely concrete end of the scale than at the extremely abstract end. This distribution of concepts suggests that mid-scale noise is not responsible for the relationship between interoceptive strength and concreteness ratings, and that abstract concepts are more likely than concrete concepts to rely on interoception.

Finally, a greater proportion of abstract concepts (13.6%) than concrete concepts (3.0%) were dominated by interoception. Of the 2781 concepts that were interoceptively dominant, the largest share were very abstract ($N = 1213$, 43.6%) or somewhat abstract ($N = 1109$, 39.9%), whereas a much smaller number were very concrete ($N = 103$, 3.7%) or somewhat concrete ($N = 356$, 12.8%). By contrast, of the 29 448 concepts dominated by modalities other than interoception, the smallest share were very abstract ($N = 5313$, 18.0%), a large number were somewhat abstract ($N = 9494$, 32.2%), but almost half were either somewhat concrete ($N = 7261$, 24.7%) or very concrete ($N = 7380$, 25.1%). Concrete concepts that were dominated by interoception tended to focus on physiological entities or effectors that could also be perceived outside the body, such as fatigue, pain and illness, gastrointestinal (mal)function and drugs. For instance, the five most concrete interoceptively dominant concepts were *valium*, *poop*, *pancreas*, *windpipe* and *intestines*, all of which had moderate interoceptive strength ratings. Abstract concepts

Table 2. Number and examples of concepts across categories of interoceptive strength for abstract and concrete concepts.

	concreteness							
	very abstract		somewhat abstract		somewhat concrete		very concrete	
interoceptive strength	*N*	examples	*N*	examples	*N*	examples	*N*	examples
weak	3542	aptitude, democracy, suggest	7416	century, popular, syntax	6336	healthcare, pink, zone	6895	chair, food neuroscientist
moderate	2828	belief, optimal, wrong	2854	genuine, nightmare, shy	1134	asthma, rehab, warm	542	baby, guard pregnant
strong	156	excite, serenity, sadness	333	anger, love, sleepy	147	nausea, pain, thirst	46	breathing, morphine, sex

that were dominated by interoception tended to come from a wider variety of domains that incorporated those of concrete concepts and additionally included concepts related to emotion and cognition. For example, the five most abstract interoceptively dominant words were *spiritually*, *belief*, *enlightening*, *intuitively* and *ambivalent*, all of which were moderately or strongly interoceptive.

In summary, interoceptive experience provides a potential means of grounding concepts across the full spectrum of concreteness, but appears to be more important to abstract concepts than to concrete concepts. At least some of this difference emerges from the fact that emotion concepts, which are overwhelmingly abstract both in participant judgements and theoretical assumptions (e.g. [3,28,31–33]), tend to be strongly reliant on interoception. We examine the interoceptive nature of emotions in more depth in the next study.

4. Study 2: interoception in emotion concepts

A growing body of evidence (e.g. [9,11,14]) points to a relationship between emotional and interoceptive experience, which suggests that interoception may be particularly important in the grounding of emotion concepts. Our second study, therefore, aimed to explore the importance of interoceptive experience to emotion concepts, including concepts belonging to different emotion categories.

(a) Method

(i) Materials

Five hundred and forty-seven emotion concepts were compiled from the perceptual strength norms used in Study 1. Thirty-one prototypical emotion words [34] were initially selected as the core item set, and we then identified multiple associated lemmas for each root word (e.g. 'sadden', 'sadly' and 'sadness' for the root word 'sad') and additional related emotion concepts via a thesaurus. Any ambiguous words with a secondary meaning that related to a non-emotion concept (e.g. 'irritation' can refer to a skin irritation as well as an emotional state) were excluded.

We also selected 547 non-emotional abstract concepts to act as matched controls (e.g. *condemn*, *heaven*), which were matched individually to the emotion concepts on concreteness ratings [28] and predominant word class (i.e. verb, noun, adverb or adjective). Five emotion concepts fell just above the midpoint of the concreteness scale with ratings between 3.00 and 3.13 (e.g. *rage*), as did six control concepts (e.g. *destroy*), but as these items represent only 1% of the dataset we continue to refer to the items as abstract for convenience. Concreteness ratings were on average 2.01 (s.d. = 0.33) for emotion concepts and 2.00 (s.d. = 0.33) for abstract control concepts. We also made a simultaneous effort to match on valence but ratings were available for only 240 emotion concepts [35], for which we selected a non-emotion concept with a similar valence rating to act as a matched control (e.g. emotion concept *angst* matched with non-emotion control *trickery*). We estimated the valence of a further 234 emotion concepts from their lemmas (e.g. valence rating for *anxiously* based on that for *anxious*) and then selected non-emotion matched controls as above (e.g. *incoherently*). We classified a final 73 concepts as positive or negative valence based on their core emotion category (i.e. *anger*, *fear*, *disgust* and *sadness* words were classed as negative; *love*, *happiness* and *surprise* words were classed as positive [34,36]) and then selected a non-emotion matched control from the same valence class (e.g. *perturbed* was classified as negative valence so we selected non-emotion negative concept *deceptive* as a matched control).

(ii) Design and analysis

We conducted exploratory analyses with two goals in mind: to determine the importance of interoception relative to other perceptual modalities in emotion concepts compared to abstract control concepts, and to examine whether and how the contribution of interoceptive information differed across emotion categories. For the latter analysis, we categorized emotion concepts into subgroups of seven core categories: anger ($N = 35$), disgust ($N = 33$), fear ($N = 57$), happiness ($N = 66$), love ($N = 31$), sadness ($N = 62$) and surprise ($N = 21$). Not all emotion words could be unambiguously categorized in this way (e.g. *envy* does not belong to one of the above categories), and such words were excluded from the category analysis. As in Study 1, these analyses were exploratory and no inferential statistics are reported.

(b) Results and discussion

(i) Interoception in emotion versus other abstract concepts

The majority of emotion concepts (64.0%, $N = 350$) were dominated by interoception, in contrast to a much smaller proportion of abstract control concepts (16.3%, $N = 89$). The

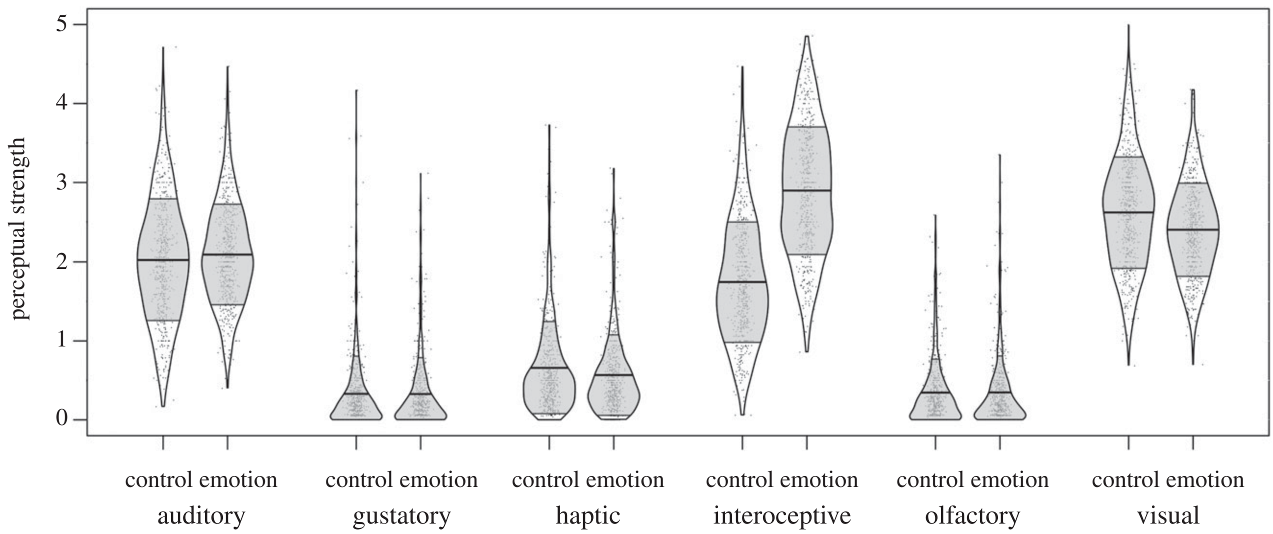

Figure 2. Distribution of modality-specific perceptual strength ratings for emotion concepts and for matched control concepts of equivalent abstractness and valence. Grey shaded areas represent one standard deviation each side of a central mean line.

remainder of emotion concepts were dominated by vision (22.9%, $N = 125$) and audition (12.8%, $N = 70$), while these modalities predominated in abstract control concepts (vision: 61.4%, $N = 336$; audition: 21.0%, $N = 115$). Less than 1% of all concepts from both groups were dominated by gustatory, haptic or olfactory information. For emotion concepts, mean interoceptive strength was higher than all other sensory modalities, and, indeed, was higher than interoceptive strength for abstract controls (figure 2). The magnitude of interoceptive strength for abstract control concepts in this study ($M = 1.75$, s.d. $= 0.76$) was higher than that found in Study 1 for all abstract concepts ($M = 1.34$, s.d. $= 0.89$), possibly due to controlling concreteness, valence and word class, but interoceptive strength for emotion concepts was markedly higher again ($M = 2.90$, s.d. $= 0.81$). These data suggest that interoception is the most important perceptual modality in the experience of emotion concepts, and that emotions appear to rely on interoceptive information moreso than other, non-emotion abstract concepts.

(ii) Interoception across emotion categories

While interoception was at least moderately important to all categories of emotion, its importance varied across individual categories (figure 3). Interoceptive strength was highest for *fear*, followed by *sadness*, *happiness*, *love*, *anger*, *disgust* and *surprise*. Examination of interoceptive dominance showed a slightly different pattern, where interoception tended to be more important to negative categories of emotion than to positive categories. The negative emotion categories most dominated by interoception were *fear* (86.0%, $N = 49$) and *sadness* (85.5%, $N = 53$), followed by a majority of concepts in *disgust* (54.5%, $N = 18$) and lastly *anger* (40.0%, $N = 14$). On the positive side, most concepts in *happiness* were interoceptively dominant (65.2%, $N = 43$), but there was a smaller proportion for *love* (41.9%, $N = 13$) and *surprise* (38.1%, $N = 8$). Finding that interoception was extremely important for concepts relating to the emotions of *fear* and *sadness* is consistent with work linking interoception to depression [12], anxiety [14] and panic disorder [37]. Nonetheless, interoception was important to the experience of all core emotion categories, even where it did not dominate, which suggests that the description of emotions as 'visceral' may be

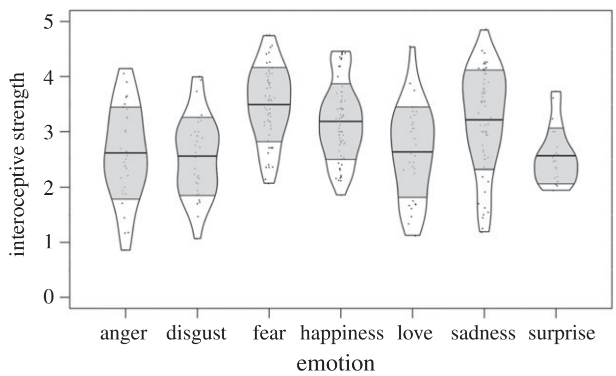

Figure 3. Distribution of interoceptive strength ratings for categories of core emotion concepts. Shaded areas represent one standard deviation each side of a central mean line.

a literal truth. That is, emotion concepts such as *grieving*, *terror* and *bliss*, which are usually categorised as abstract, are largely experienced—and potentially grounded—through sensations inside the body.

5. Study 3: interoception and concreteness effects

Although Studies 1 and 2 showed that interoception is important to how people experience both abstract and concrete concepts, particularly (but not exclusively) emotions, how can we be certain that interoceptive information contributes to conceptual grounding? It could be argued that the apparent importance of interoceptive strength is simply an artefact of having asked people to think explicitly about an unusual sensory modality, but that it does not normally play an important role in the grounded representation of concepts. In this final study, we aimed to ascertain whether interoceptive information contributes to concreteness effects in word recognition, a phenomenon that results from automatic and implicit access to the grounded semantics of words.

Concreteness effects are a form of semantic facilitation whereby words that refer to concrete concepts are processed more quickly and accurately than those referring to abstract concepts (e.g. [38,39]). Recently, we have shown that maximum perceptual strength (i.e. strength in the dominant modality) is

Table 3. Log Bayes factors (BF) for regression model comparisons of each maximum perceptual strength predictor against the null (lexical) model, and for the inclusion of interoception against its exclusion, for standardized RT and accuracy in lexical decision and word naming tasks.

		lexical decision		word naming	
maximum perceptual strength	model comparison	RT	accuracy	RT	accuracy
five traditional modalities	BF_{10}	100.978	36.834	43.335	48.978
six modalities including interoception	BF_{20}	137.949	58.101	58.194	63.984
benefit of interoception	BF_{21}	36.791	21.267	14.859	15.006

the best available predictor of concreteness effects in word recognition, whereby strongly perceptual words are recognized more easily than weakly perceptual words [21,23]. To date, maximum perceptual strength has been based only on the five traditional sensory modalities (i.e. hearing, sight, touch, taste and smell), without incorporating interoception. If interoceptive information is important to the grounding of conceptual content, then including it in the calculation of maximum perceptual strength will predict semantic facilitation better than basing dominance on the five traditional sensory modalities. By contrast, if interoceptive information does not play an important role in conceptual grounding, then its inclusion will make little difference to the ability of maximum perceptual strength to predict semantic facilitation in word recognition.

(a) Method

(i) Materials

We used data from the English Lexicon Project (Elexicon: [40]) to provide lexical decision and word naming response times (RT: standardized response times with individual variance removed) and accuracy (proportion correct responses) for each word. Of our original 32 229 concepts, 19 041 had available data in Elexicon, split almost evenly between abstract ($N = 9518$) and concrete ($N = 9523$) concepts, and with a similar proportion of interoceptively dominant concepts to the full dataset (9.0%). We also extracted lexical characteristics from Elexicon to act as predictors, as described below.

(ii) Design and analysis

For each dependent variable (RT and accuracy per lexical decision and word naming task), we ran Bayesian linear regression analyses with non-informative default priors (r scale covariates = 0.354 [41]) to determine whether the data were better modelled by including or excluding interoception from the calculation of maximum perceptual strength.

Analyses comprised two hierarchical steps. Step 1 determined a basic lexical model: rather than specify a compulsory set of lexical predictors for all analyses, we allowed the data to determine the most appropriate subset of lexical predictors for each dependent variable. We entered candidate lexical predictors that commonly contribute to word recognition performance (log SUBTLEXus word frequency, length in letters, number of syllables, orthographic neighbourhood size, phonological neighbourhood size, orthographic Levenshtein distance, phonological Levenshtein distance) and calculated the Bayes factor (BF_{10}) for each subset relative to the best model. We then selected the best model to go forward to the next step where there was good evidence it was superior to the second-best model ($BF_{10} <= 0.333$), or, where the best and second-best models were not clearly distinguishable (second-best model $BF_{10} > 0.333$), we selected the model with fewer parameters. Step 2 entered one of our two semantic predictors of interest: maximum perceptual strength across the five traditional modalities (i.e. highest rating of auditory, gustatory, haptic, olfactory and visual strength) and maximum perceptual strength across six modalities including interoception (i.e. highest of the six modality-specific ratings).

Owing to the magnitude of the BF values, we report natural log BFs for the Step 2 model comparison of each maximum perceptual strength predictor relative to the null model of Step 1 (log BF_{10} for five traditional modalities; log BF_{20} for six modalities including interoception) and for the comparisons between the two competing Step 2 models of maximum perceptual strength across six modalities including interoception relative to five traditional modalities (log BF_{21}).

(b) Results and discussion

Maximum perceptual strength across the five traditional modalities was an excellent predictor of word recognition performance, but maximum perceptual strength *including* interoception outperformed it across all measures (table 3). For both RT and accuracy in both lexical decision and word naming, the data were log 15–37 times more likely when maximum perceptual strength incorporated interoception than when it excluded it. These results constitute very strong evidence [42] that interoceptive strength improves the ability of maximum perceptual strength to predict concreteness effects in word recognition. Interoceptive information, therefore, forms part of the semantic content that is automatically activated on presentation of a word, and its importance in Studies 1–2 is not a mere artefact of an explicit rating task. In short, the present results indicate that interoception contributes to the perceptual grounding of concepts.

6. General discussion

In a series of exploratory analyses on a megastudy dataset, we examined the role of interoception in the perceptual grounding of concepts. In Study 1, we analysed over 32 000 concepts and found that interoceptive strength (i.e. the extent to which a concept is experienced through sensations inside the body) captures distinctive perceptual information that is important to a wide range of conceptual domains, including physiological functions (e.g. *heartbeat*, *breathing*, *hunger*, *thirst*, *heatstroke*, *orgasm*, *pain*, *fatigue*), illness (e.g. *diabetes*, *flu*), drugs (e.g. *caffeine*, *heroin*), cognition (e.g. *belief*, *think*) and emotion (e.g. *fear*, *joy*, *love*). In particular, interoception is more important to abstract concepts than to concrete concepts, dominating 13.6% of abstract concepts compared to only 3.0% of concrete concepts. In Study 2, we investigated a subset of over 500 emotion concepts and found that interoception is the most important perceptual modality in the experience of emotions (moreso than other concepts of similar abstractness), particularly dominating those relating to *fear* and *sadness*. Finally, in Study 3, we showed that interoception improved the ability of maximum perceptual strength (i.e. strength in the dominant perceptual modality) to predict concreteness effects in word recognition, a task where access to conceptual content is automatic and implicit, which indicates that interoception forms part of the perceptual information that comprises the referent concept. Taken together, our findings suggest that interoception has comparable status to other modalities in contributing to the perceptual grounding of concepts, particularly abstract concepts and particularly emotion concepts.

These findings raise the question of whether we should really be considering concepts like *love*, *serenity* and *thought* as abstract when they have such a strong sensory component. Contrary to conventional definitions of abstract concepts (i.e. that their referents are not particularly experienced via the senses: (e.g. [3,28,32])), we found that abstract concepts were *more* strongly interoceptive, and *more* likely to be dominated by interoceptive experience, than concrete concepts. For instance, the concepts of *hopelessness*, *mood*, *vitality* and *willpower* are all extremely abstract (ratings between 1 and 2 on a 1–5 concreteness scale) and yet are simultaneously very strongly experienced as sensations inside the body (ratings between 4 and 5 on a 0–5 interoceptive strength scale). It is similarly possible to identify other examples of very abstract concepts that are nonetheless strongly experienced by other modalities, including hearing (e.g. *verbose*) or vision (e.g. *fashionable*). Clearly, abstract cannot mean non-perceptual.

One possible explanation for this conflict is that the abstract/concrete distinction does depend, at least in part, on how much a concept is grounded in perceptual experience, but that people have been hitherto mistaken as to which concepts are minimally experienced via the senses. Recent research from our laboratory has shown that people are generally not very good at assessing their sensory experience of a concept without losing a large amount of perceptual information in the process [23]. Unless attention is explicitly drawn to each modality individually, participants instead tend to focus on visual (and to a lesser extent, olfactory) experience but neglect or distort information from auditory, haptic and gustatory modalities. We did not consider interoception in that study, but it is plausible that it too may be subject to such neglect or distortion. The net effect is that, whenever people consider the abstract/concrete distinction on the basis of sensory experience, they most likely fail to consider all relevant sensory information, and so many strongly perceptual concepts end up erroneously categorized as abstract. If this explanation is correct, then concepts like *love* (indeed, emotion concepts in general), *thought* and *fashionable* would not be abstract because they are strongly perceptual. Only concepts that are weak across all perceptual modalities, such as *year*, *hydrogen* or *plausibly*, would be truly abstract. However, such an explanation is not entirely consistent with the fact that some weakly perceptual concepts are nonetheless considered to be highly concrete. For instance, the concepts of *month*, *cyanide*, *bacteria* and *brainstem* are all extremely concrete (ratings between 4 and 5 on a 1–5 concreteness scale) and yet are simultaneously weakly experienced by all perceptual modalities (ratings between 0 and 2 on a 0–5 perceptual strength scales). An alternative explanation might be that the abstract/concrete distinction does not rest on the relative extent of perceptual grounding, but rather depends on the extent of objectivity: abstract concepts have a subjective existence inside the mind whereas concrete concepts have an objective existence that is independent of the mind (e.g. [43,44]). Such a distinction would allow abstract concepts like *love*, *thought* and *fashionable* to be grounded in perceptual experience but still retain their abstractness because their existence is essentially subjective. Similarly, concrete concepts like *cyanide*, *bacteria* and *brainstem* could have little perceptual grounding but yet retain their concreteness because of their objective existence. However, this account is not entirely consistent with how concepts fall on the abstract/concrete spectrum. If *month* is very concrete because of its objective existence (arguably, a complete lunar cycle), then why is *year* (a complete solar cycle) very abstract? Similarly, the chemical elements of *hydrogen*, *oxygen* and *helium* are all considered abstract despite their objective existence.

In summary, although the abstract/concrete distinction has a long history as an ontological framework, its basis is unclear. Certainly, it does not align well with perceptual grounding. A very large number of concepts that are traditionally considered to be abstract are experienced via the senses of vision, hearing, touch, taste, smell and now interoception. As we show in the present paper, the importance of interoception in particular must not be ignored any longer, given its greater contribution to abstract concepts than to concrete and its role as the most important perceptual modality in emotion concepts. More research is necessary to reconcile abstractness with perceptual grounding.

Ethics. Ethical approval was obtained from Lancaster University Research Ethics Committee. Informed consent was obtained from all participants.

Data accessibility. The datasets supporting this article are available via the Zenodo repository: http://dx.doi.org/10.5281/zenodo.1039314 (see [29]).

Authors' contributions. L.C. and D.L. conceived the study and compiled the data; L.C. and B.B. analysed the data; L.C. and D.L. took the lead in writing the article, with contributions from B.B. All authors gave final approval for publication.

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