Tactile cognition in rodents

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ABSTRACT

Since the discovery 50 years ago of the precisely ordered representation of the whiskers in somatosensory cortex, the rodent tactile sensory system has been a fertile ground for the study of sensory processing. With the growing sophistication of touch-based behavioral paradigms, together with advances in neurophysiological methodology, a new approach is emerging. By posing increasingly complex perceptual and memory problems, in many cases analogous to human psychophysical tasks, investigators now explore the operations underlying rodent problem solving. We define the neural basis of tactile cognition as the transformation from a stage in which neuronal activity encodes elemental features, local in space and in time, to a stage in which neuronal activity is an explicit representation of the behavioral operations underlying the current task. Selecting a set of whisker-based behavioral tasks, we show that rodents achieve high level performance through the workings of neuronal circuits that are accessible, decodable, and manipulatable. As a means towards exploring tactile cognition, this review presents leading psychophysical paradigms and, where known, their neural correlates.

1. Introduction

Entering a busy marketplace, we might describe a scene of flowing crowds and stalls full of merchandise. It is inconceivable that we would experience the moment by its parameters of luminance, contrast, spatial frequency, wavelength. Likewise, when we stroke a fabric, we might describe lush velvet, but not the high-frequency vibration transduced by our fingertips' tactile receptors. We experience things and people, objects and animals, not a confusing overflow of physical signals. In short, we perceive the world more than we sense it.

Since direct access to neurons in humans is limited to the clinical context (Quian Quiroga et al., 2008), advances in understanding the neuronal mechanisms of perception typically occur after investigators develop parallels between the behavioral capacities in the primate repertoire and those of simpler mammals. For instance, the discovery in rats of the contribution of the hippocampus to the very human-like behavior of navigating to spatial locations (Morris et al., 1982) led to the exploration of the human hippocampus first as a structure involved in navigating physical space (Maguire et al., 2000) and later as a structure involved in navigating the semantic space of knowledge (Viganò and Piazza, 2020).

Until some 10 years ago, neuroscientists attributed a wide range of perceptual functions to primates but not to rodents. While many studies had taken advantage of innate rodent behaviors – e.g. exploring a novel object (Lueptow, 2017) – behavioral paradigms where training might require a multi-stage shaping regime were rarely developed. However, as methodologies adapt to natural deportment, rodents have been found to express a surprising range of abilities. Rats spontaneously recognize an object even when views differ by angle, size, and position (Zoccolan et al., 2009; Tafazoli et al., 2012); such generalization is a hallmark of authentic visual perception and was once believed to belong only to primates. Rats hold stimuli in working memory with performance akin to that of humans and monkeys (Fassihi et al., 2014), integrate separate sensory modalities to create a supramodal object representation (Raposo et al., 2012; Nikbakht et al., 2018), assess reward statistics (Karlsson et al., 2012), indicate their degree of confidence in the outcome of their choices (Lavan et al., 2011), and extract a rule from specific task and generalize it to novel experiences (Murphy et al., 2008; Kuchibhotla and Bathellier, 2018). In sum, mice and especially rats are ever more fulfilling their promise of expressing high level sensory-perceptual cognition (Carandini and Churchland, 2013); importantly, they achieve such cognition through the workings of neuronal circuits that are accessible (Summerson and Kemere, 2015), decodable (Panzeri et al., 2017), and manipulatable (Yizhar et al., 2011).

In this review we highlight behavioral paradigms grounded in the tactile perceptual capacities of rats and mice. Tactile cognition, in our

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framework, occurs with the emergence of neuronal activity that constitutes an explicit representation of a behaviorally relevant object or event. A particularly intriguing form of cognition occurs in the process of recognizing external inputs not merely as sensory data but as the signatures of meaningful things occupying physical space in the external world. For some of the behavioral paradigms presented here, it is possible to draw together a number of approaches – psychophysics, electrophysiology and imaging, optogenetics – to discern the key computations giving rise to explicit representations of behavior.

2. Early work identifying cerebral cortex with sensory perception

The unique function of cortical processing in subserving perceptual cognition was uncovered almost 140 years ago. We begin by discussing ideas matured in the course of studying vision and audition, as these are relevant to touch. Hermann Munk proposed that the cerebral cortex is responsible for the difference between seeing elementary forms and perceiving objects (Munk, 1881). His subjects were dogs who received either a lesion restricted to the posterior pole of the occipital lobe or else a lesion elsewhere, including regions farther anterior and lateral (angular gyrus). Those with bilateral occipital lobe ablation showed complete blindness, bumping into tables and walls. Those with more anterior lesions, sparing the occipital pole, did not collide with furniture, yet did not recognize by vision previously familiar objects. This condition was described by Munk as "cortical blindness," interpreted as the failure of the cerebral cortex (having been deprived of some essential volume of tissue) to create mental representations of visual sensations. Though the details of the lesion sites have been disputed (Fishman, 1995), the connection between cortical damage and agnosia (loss of sensory understanding) remains valid.

In the one-hundred years following Munk's (1881) publication, behavioral methodologies became more systematic and quantitative. Whitfield's synthesis (Whitfield, 1979) remains extraordinarily insightful even today. He noted that a cat with its auditory pathway ablated above the level of the brain stem can localize sound; it can be trained to react when a sound is presented to its right, and to inhibit that reaction when a sound is presented to its left (Axelrod and Diamond, 1965). Thus, pre-cortical processing stages can transmit left/right differences in neuronal firing to the centers that control licking. But the same decorticate animal cannot be trained to approach a sound source, once localized, on the other side of the room (Diamond et al., 1956). Whitfield interpreted the deficit as a failure to transform "sensory data" into "objects" within the surrounding world. Animals could perform high-acuity sensory discriminations even after ablation of sensory cortex, provided the task does not require them to treat the sounds as emanating from real things in the world.

Precisely what functions are missing in the lesioned animal? Additional experiments provide clues (Fig. 1). Cats with cortex intact act upon two different stimulus conditions (Fig. 1A: Tasks 1 and 2 in large box) as if the sound is on the left (depicted by speaker pointing to left ear). Once trained to respond differentially to clicks played to the left ear-only versus right ear-only (Task 1), they can immediately transfer the learning to a new task, namely, to respond differentially if the left-ear clicks precede the right-ear clicks by 100 μs versus the opposite temporal order (Task 2).

After auditory cortical ablation (depicted by the red X in Fig. 1B), an animal can learn both tasks, but they are learned as two separate problems, with no transfer between them (Masterton and Diamond, 1964). To a human listener, and presumably to a cortex-intact animal, what is in common to Tasks 1 and 2 is that the sound seems to originate in the left or right egocentric space, even if the firing patterns evoked in the two paradigms are quite different. In the auditory brain stem, real-world lateralized sounds evoke both a left/right difference in response magnitude and a left/right temporal order. Perhaps an animal with cortex intact interprets the two distinct click paradigms as a unique task – to find the position of a sound source in space – and transfers between tasks whether position is encoded by the amplitude difference or temporal order. A deficit appears in the decorticate animal when it is not able to endow the simple click-evoked sensations with the quality of
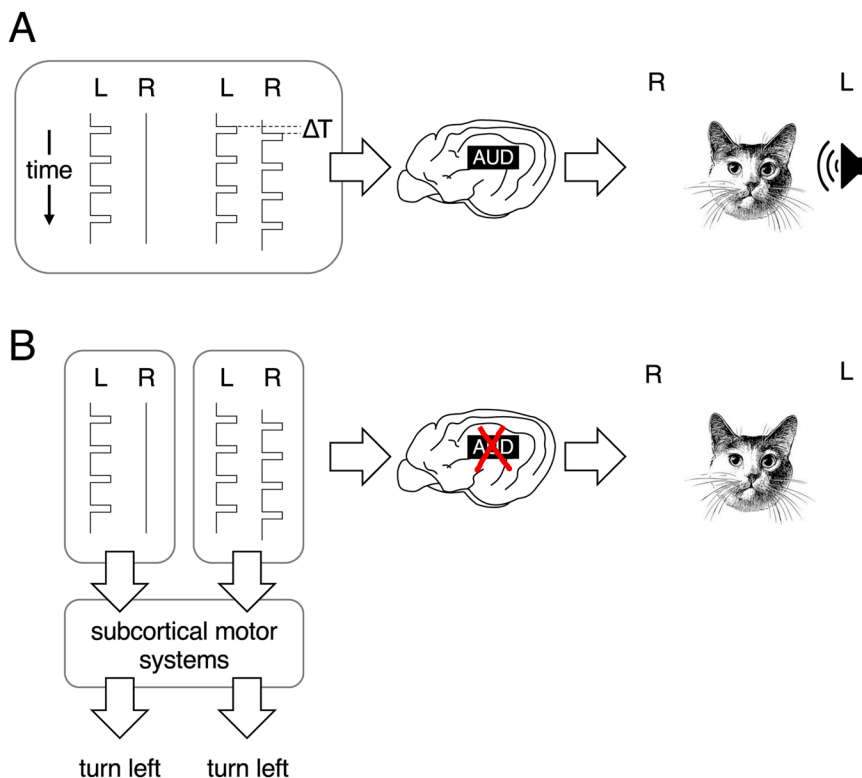
Fig. 1. Behavioral deficit associated with auditory cortical lesion. (A) The box shows two tasks defined by two stimulus conditions, each condition consisting of sounds delivered separately to the left (L) and right (R) ears through earphones. In task 1, sounds (clicks, shown as square pulses) are presented to one ear only (here L), with the other ear (here R) silent. In task 2, sounds are presented to both ears, but one side precedes the other by a small time step, DT (here L clicks precede R clicks). Through auditory cortical processing (AUD), both stimulus conditions are perceived as a sound in left egocentric space and the cat responds to the left. Training in one task transfers immediately to the other. (B) Animals with auditory cortical lesion can learn one task but show no learning transfer to the other task. It appears that the capacity to act through subcortical motor systems is intact, but the two different stimulus configurations fail to evoke the mental representation of a real sound source in external space. Based on results of (Masterton and Diamond, 1964).

belonging to external objects, as represented by the absence of the speaker in Fig. 1B. Because the lesioned animal interprets the two click paradigms as two distinct sensations rather than as features of a real object, the learning is not transferred.

Generalizing this notion to all modalities, Whitfield suggested that even with sensory cortex ablated, animals can act on the information present in subcortical centers provided the task can be solved when motor systems read out the elemental physical characteristics of a stimulus (tone, wavelength, vibration frequency) as a neuronal activity pattern within the brain. Subcortical motor systems, while likely engaged with cortex intact (Fig. 1A), become the essential processing circuits and are unable to generate the feeling of "sound on the left." Whitfield concluded (p. 146), much like Munk, that the cortex transforms physical characteristics into the percept of real things that are "out there" in the world.

While recognizing that the behavioral changes engendered by ablation and its modern counterpart, optogenetic intervention, are not straightforward to interpret inasmuch as the manipulation affects processing in areas connected to the targeted site (Otchy et al., 2015), the parallels between intervention methods and human neuropsychology (Shallice, 1988) make them invaluable. In rodent tactile studies, the role of cortical processing can also be deduced when the information necessary to perform the task is not *explicitly encoded* in the neuronal firing of the first cortical processing stages, vibrissal primary and secondary somatosensory cortex (vS1 and vS2, respectively). When vS1 and vS2 encode only *incomplete* components of the final percept, the neuronal substrate underlying behavior must reside in some downstream center (cortical and/or subcortical regions including thalamus, basal ganglia and cerebellum) which elaborates the early cortical signals. After a brief overview of the functional organization of the pathway from whiskers to sensory cortex, the remaining sections consider the involvement of cortical processing in various forms of tactile cognition.

3. From whiskers to sensory cortex

Typically occupying dark environments, rodents rely on tactile signals generated through their facial whiskers (vibrissae). The first laboratory study dates to 1912, when Stella Vincent showed that rats, after having their whiskers clipped, navigate through a maze slowly, and frequently turn down the wrong arm on their way to the endpoint (Vincent, 1912). Recent work has emphasized the dual modes of vibrissal information acquisition: generative, where the animal sweeps its whiskers forward and backwards to palpate objects, and receptive, where the animal keeps its whiskers still, and collects mechanical signals from the motion of an object such as a vibrating surface (Diamond and Arabzadeh, 2013).

In 1970 a classical study showed that each whisker on the snout is associated in mouse vS1 with a compact cluster of neurons in layer 4 (Woolsey and Van der Loos, 1970). On the basis of their wine cellar-like appearance in a tangential slice, this array of clusters was termed the "barrel field", with one barrel associated with each whisker (Fig. 2A). The barrel diameters range from roughly 200–300 μm in diameter; whisker follicles containing more receptors give rise to larger barrels (Welker and Van der Loos, 1986). Shortly after the discovery of the barrel organization in mice, a similar (though proportionately larger) structure was found in rats (Welker and Woolsey, 1974). The whiskers and barrel maps are organized similarly in rats and mice, and the same mapping terminology was adopted. Thus, whisker C3 projects densely to vS1 barrel C3.

Whisker follicles are replete with mechanosensitive nerve endings of a wide variety of morphologies (Rice et al., 1986). The relation between receptor morphology and response properties, well known in the primate skin (Paré et al., 2002), is only beginning to be worked out for the whiskers (Severson et al., 2017). Parallel pathways convey signals from the whiskers to the cerebral cortex (Yu et al., 2006). The lemniscal
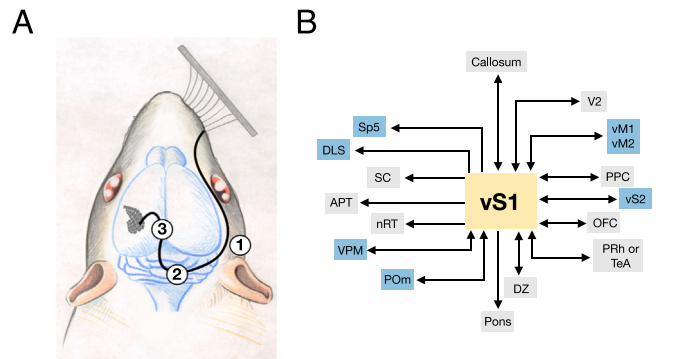
Fig. 2. Organization of the rodent whisker system. (A). The right vibrissae are depicted as if in contact with a vibrating plate, the paradigm for the experiment results of Figs. 5, 7 and 8. Any mechanical energy transmitted through the whisker to the follicle triggers a chain of activity transmitted by the mechanoreceptive trigeminal ganglion neurons (**1**) to the trigeminal brainstem nuclei (**2**) to the thalamic nuclei (**3**) and from there to vS1. In this primary sensory cortical "barrel field", individual whiskers are matched to individual barrels shown, each shown as a gray oval. (B). A summary of the brain regions connected with vS1. Blue-highlighted boxes are those with denser connections. Note that most connectivity is reciprocal (double-headed arrows) while some is unidirectional (single-headed arrows). APT, anterior pretectal nucleus; DLS, dorsolateral striatum; DZ, dysgranular zone surrounding vS1; nRT, nucleus reticularis of the thalamus; OFC, orbitofrontal cortex; POm, posterior medial nucleus of the thalamus; PPC, posterior parietal cortex; PRh, perirhinal cortex; SC, superior colliculus; Sp5, spinal trigeminal nuclei; TeA, temporal association cortex; vM1, whisker-related primary motor cortex; vM2, whisker-related secondary motor cortex; vS2, whisker-related secondary somatosensory cortex; VPM, ventral posterior medial nucleus of the thalamus; V2, secondary visual area. Figure inspired by (Petersen, 2019).

pathway relays information from the principal trigeminal nucleus of the brain stem to the contralateral ventral posteromedial thalamic nucleus (VPM) and then to primary vibrissal somatosensory cortex, vS1. The paralemniscal pathway relays information from the spinal trigeminal nucleus (pars interpolaris, rostral part) to the posterior medial thalamic nucleus (POm) and then to vS1 and to the secondary vibrissal somatosensory cortex, vS2. The extralemniscal pathway relays information through the spinal trigeminal nucleus (pars interpolaris, caudal part) and VPM to vS1 and vS2. Any mechanical energy transmitted into the follicle – originating in e.g. whisker deflection, bending, pulling, or vibration – evokes a volley of activity in trigeminal ganglion neurons (the neurons whose terminals are in the follicle), and successively along the pathways outlined above. The distinct functional properties characterizing the three main pathways are the object of ongoing study and are not yet fully understood (Moore et al., 2015).

Incoming sensory information is processed in neuronal microcircuits in vS1 (Petersen, 2019; Staiger and Petersen, 2021) and distributed to downstream cortical and subcortical brain regions by direct projections (Fig. 2B). The functional properties and connectivity of vS2 have been examined less, and most of the studies in the present review concern vS1.

4. Behaviors that are conserved or lost after cortical ablation

To introduce the problem of rodent tactile cognition, it is useful to ask what does and does not depend on cortical processing. Because a rodent's initial encounter with an object is commonly a brief vibrissal contact, whisker deflection in controlled experimental conditions has been taken as a proxy for the first step in object exploration and navigation. When mice learn to lick a reward spout in response to a brief (<10 ms) deflection of a single whisker, neuronal recordings in vS1 reveal an early (<50 ms) sensory response and a secondary, late (50–400 ms) depolarization; the late response is enhanced on hit trials compared to misses (Sachidhanandam et al., 2013; Petersen, 2019).

Optogenetic and pharmacological inactivation of vS1 decreases hit rates (Guo et al., 2014). However, from the engagement of vS1 in the detection of vibrissal motion, it does not necessarily follow that this behavior requires vS1 under all conditions.

Rats can learn to cease licking (i) at the onset of an oscillation in the air stream delivered to a single vibrissa, or (ii) at the time of change in the frequency of oscillation, if the relevant event (onset or change) predicts the delivery of an electrical shock (Hutson and Masterton, 1986). This behavior is unaffected by ablation of the vS1 territory of the whisker receiving the air stream (Hutson and Masterton, 1986). In mice trained to lick for vibrissal deflection, the deficit in detection caused by transient optogenetic vS1 inactivation, as well as by permanent lesions, is greatly reduced by the time of the subsequent session (Hong et al., 2018) indicating recovery of function even without cortical contributions. Ablation of the vS1 before learning does not affect task acquisition.

In the studies cited above, the sensory features to be acted on are explicitly encoded at early stages of the sensory pathway (Arabzadeh et al., 2005; Stüttgen et al., 2006; Petersen, 2019; Staiger and Petersen, 2021); in the absence of sensory cortex, the tasks apparently can be solved when motor systems gain access to the subcortical neuronal activity patterns that encode the elemental physical characteristics of the stimulus. From this reasoning, we predict that instantaneous change-detection tasks (Waiblinger et al., 2015) could be solved after sensory cortical ablation. In our view, detecting a deflection or sensing the instantaneous change in some prominent kinematic feature are behaviors that may be supported by subcortical systems, inasmuch as they require neither integration over time or space nor the interpretation of something "out there."

By contrast, a number of behaviors are never recovered after vS1 interruption. One of these is gap crossing (Fig. 3) (Hutson and Masterton, 1986; Harris et al., 1999, 2001; Harris and Diamond, 2000; Diamond et al., 2001, 2003). Perched on a platform, without visual cues, a rat learns to feel a platform positioned across a gap whose span is varied from trial to trial. After leaning forward and palpating the opposite platform with as few as a single whisker (e.g. C1), the rat steps or jumps across the gap to receive a reward (Fig. 3A). If the reward platform is out of whisker-reach, the rat tries to make contact but, failing to do so, remains on the start platform (Fig. 3B). Ablation of the single whisker's topographically connected column (e.g. C1) in vS1 makes the rat unable to use whisker contact to initiate the gap crossing (Hutson and Masterton, 1986). Though the rat palpates the target platform – and even

crosses if it makes nose contact – the platform seems not to exist when touched by the whisker (Fig. 3C). No amount of training can overcome this "tactile agnosia". Indeed, gap-crossing performance after column C1 ablation is indistinguishable from the condition in which the C1 whisker itself is trimmed. We speculate that when the vS1-lesioned rat palpates the opposite platform, vibrissal kinematic features are encoded at subcortical levels, but transmission of touch-by-touch information through vS1 to downstream integrators is interrupted. Reverting again to the Whitfield conception of cortical processing: the vibrissal contact information encoded at subcortical levels does not evoke the mental representation of a platform "out there" in the world unless distributed within cortex. Notably, we pointed out above that sensing whisker deflection in order to lick or not-lick – which does *not* entail the perception of a real object – can be achieved by routing subcortical sensory information to motor control centers (Masterton and Diamond, 1964; Hutson and Masterton, 1986; Hong et al., 2018).

Other tasks which require rats to represent real-world objects have been designed, even if the neuronal correlates are not yet known. It is reflexive for rats to step down from an illuminated, raised platform to reach a dark, safer space. If the lower space consists of an invisible (glass) table, they will step down onto it only if they can lean over the platform edge to feel the glass with their whiskers (Schiffman et al., 1970). We speculate that with vS1 ablated or inactivated, rats would fail to step down. Also, rats can learn to use their whiskers to follow an airflow to its source across a table, getting a reward whenever they find the correct source among 5 possible locations (Yu et al., 2016). Likewise, we speculate that with vS1 ablated or inactivated, rats would fail to move to the airflow source.

5. Accumulation of evidence in texture perception

Texture perception is crucial to natural rodent behavior (e.g. (Rhodes and Richmond, 1985)). Rats in the laboratory show high discriminative capacities when judging roughness (Morita et al., 2011) or groove density (Carvell and Simons, 1990). As a rat palpates a surface (Fig. 4A) at the "whisking" frequency of about 10 touches per second (Carvell and Simons, 1990), its vibrissae (Fig. 4B) undergo a sequence of shape changes with every contact and release (Arabzadeh et al., 2005; Diamond and Arabzadeh, 2013). To obtain a more complete characterization, in a recent study (Zuo and Diamond, 2019a) we tracked the full 2-dimensional shape of single whiskers at 1-ms temporal resolution (Perkon et al., 2011) and extracted nine kinematic features. By linear
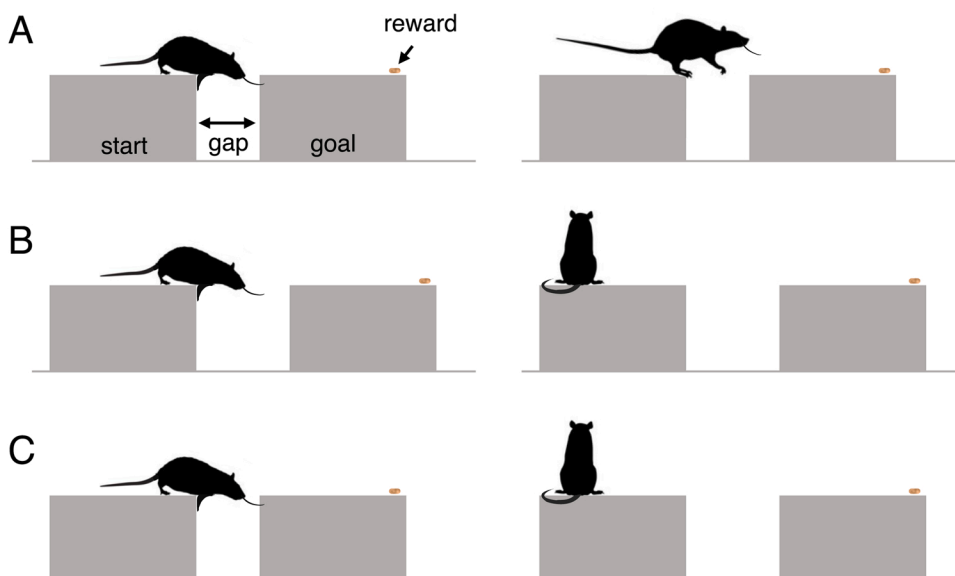
Fig. 3. Cortical dependence of gap crossing. (A). The whiskers are conserved unilaterally, with one side fully clipped. After palpating the goal platform (left panel), the rat jumps across the gap to collect a food reward. (B). If the goal platform cannot be reached with the whiskers (left panel), the rat remains on the start platform (right panel). (C). If the topographically matched cortical territory contraleral to the whiskers is ablated, even upon making contact (left panel), the rat remains on the start platform (right panel). Its performance is equivalent to that of a rat with all whiskers clipped bilaterally. The goal platform seems to not be "out there".
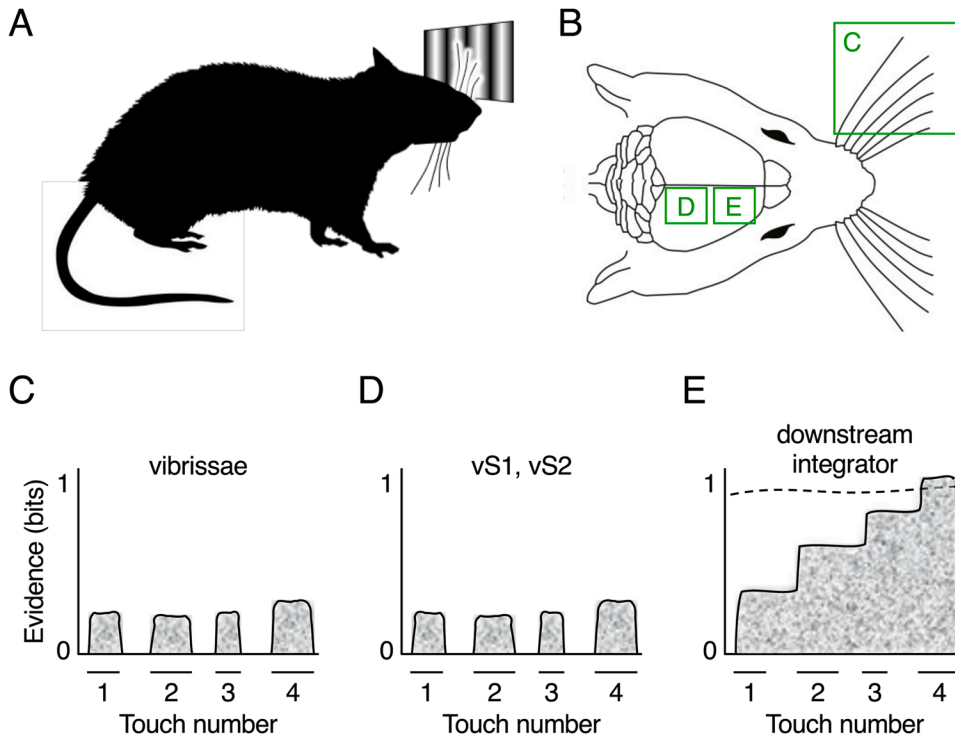
Fig. 4. Accumulation of evidence in texture perception. (A) The rat identifies the texture of a plate (in the absence of illumination) by whisking upon the surface with its left vibrissae. (B) Three stages of processing are depicted: the vibrissae (box C), contralateral cortical regions vS1 and vS2 (box D), and a posited downstream area in frontal cortex (box E). (C) Trials involve sequential contacts, at about 10 Hz. The vibrissae carry texture signals by their kinematics in information "packets", each packet derived from a single touch. In this trial, 4 sequential touches are depicted. The evidence is shown in bits, where about 1 bit of total information would be required to identify each of four distinct textures with the accuracy shown by the rats, approximately 80% correct. (D) In vS1 and vS2, neuronal populations information by texture-dependent firing rate during each touch. Contacts providing a greater vibrissal signal lead to higher information packets in somatosensory cortex. Evidence is not accumulated across touches. (E) In a posited downstream integrator, information builds up across sequential touches and is accumulated until the reaching the boundary (dashed line). At that point, the integrator holds enough evidence to support a choice with good likelihood of success, leading the rat to make a decision. Note that earlier packets of information are given more weight by the integrator. (Zuo and Diamond, 2019b, 2019a; Fassihi et al., 2020).

classification, each texture in the stimulus set was found to be associated with a unique "kinematic signature" in 9-dimensional space. When the kinematic signature on a single touch is close to the expected signature for the presented texture, the rat is likely to perform a correct identification; when the kinematic signature is closer to the expected signature of a texture that is *not* presented, the rat is more likely to make an error. These observations confirm that the kinematic features form the starting point of the percept.

The activity of neurons in vS1 and vS2 encodes whisker kinematic features (Zuo and Diamond, 2019b). Using the same linear classification methods as applied to the vibrissae, we found that the single-touch information supporting the texture present on that trial is much greater on touches taken from trials in which the rat makes the correct choice, as compared to error trials; further, rats' choices tend to match the texture supported by the largest quantity of neuronal information — whether that information is correct (matches the presented texture) or erroneous (better matches a different candidate texture).

An advantage of studying freely moving, self-paced animals is the broadened space of behavioral parameters. In texture experiments, rats show trial-to-trial variability in the way they seek and collect information, and such variability offers clues to the building up of the texture percept. They typically execute 3–7 touches per trial. If rats utilize evidence only from short time windows, as in change-detection experiments (Waiblinger et al., 2015), they may take the signal arising from a single touch as the basis for decision. Alternatively, they might accumulate evidence spanning the entire time scale of the series of touches. A number of findings support the second hypothesis (Fig. 4C). Rats' performance reaches about 70–80% correct independently of the number of touches per trial, demonstrating that they use the same total quantity of evidence on every trial. Trials comprising 4, 5, or 6 touches tend to begin with low-signal touches, whether signal is measured in whisker kinematics or in sensory cortical firing: the rat requires a larger number of touches to overcome the initial low-signal touches.

Where is the evidence integrated? The signal carried by neurons in vS1 and vS2 does not grow from touch to touch but instead encodes only the ongoing touch (shown schematically in Fig. 4D; detailed evidence in (Zuo and Diamond, 2019b)). These early-stage cortical neurons must relay information to some downstream accumulator (Fig. 4E). Although work carried out to date does not specify the identity of the downstream accumulator, it is possible to characterize its integration dynamics. The accumulator appears to summate the packets of "real-time" single-touch signals transmitted through vS1 and vS2, giving most weight to the earliest packets and progressively less weight to the successive packets – an algorithm that allows the integrator to trigger a rapid decision based on initial evidence, akin to primate visual motion decision making (Marton et al., 2019). Fitting an exponential time constant of about 100 ms to the weighting function employed by the integrator yields the same total quantity of evidence in all trials, whether a 1-touch trial or a 6-touch trial.

Texture discrimination requires vS1; ablation leads to a permanent deficit (Guic-Robles et al., 1992). Touch-by-touch integration (Fig. 4) offers a more detailed account for the dependence of texture judgment on vS1 (Guic-Robles et al., 1992) – when the vS1-lesioned rat palpates the texture, vibrissal kinematic features are encoded at subcortical levels, but transmission of information through somatosensory cortex to the downstream integrator – a necessary step in the generation of the complete texture percept – is interrupted. Although vS1 does not seem to encode the integrated evidence as it accumulates, vS1 – particularly the superficial layers – might still be casually involved in the decision-making process (Buetfering et al., 2022).

A provisional conclusion, then, is that among the forms of tactile cognition that may critically involve cortical processing are those involving the accumulation of sensory data that are distributed over time.

6. Accumulation of evidence in vibration perception

Another form of tactile cognition which involves the accumulation of sensory evidence over time is the perception of the holistic properties of a vibration. In the studies reviewed first, each vibration is composed of

low-pass filtered white noise, a sequence of speed values sampled from a half-Gaussian distribution (Fassihi et al., 2014, 2017; Esmaeili and Diamond, 2019; Toso et al., 2021a), leading to a stream of instantaneously varying features. A single vibration can be defined by its intensity, denoted I (quantified as the mean speed from onset to offset), and its duration, T. We introduced vibration perception in the context of a working memory task, where stimulus 1 and 2, separated by an interstimulus delay (ISD), are delivered to the whiskers (Fig. 5A). After a go cue, rats withdraw and select one of the two spouts, with reward location determined by the relative intensities (*intensity delayed comparison* task) or durations (*duration delayed comparison* task). Human subjects perform the same tasks, receiving vibrations on the fingertips and responding through a keyboard. First, we focus on the accumulation of evidence within single vibrations, and in Section 9 we will consider a different aspect of temporal integration – the storage and recall of the memory of stimulus 1.

In the intensity task, the stochastic nature of the vibration precludes the subject from using a "snapshot" of intensity values within a short time window to estimate the whole-vibration intensity: an ideal observer's judgment of this input stream would benefit by integrating. To assess how rats accumulate evidence to achieve a whole-vibration intensity percept, we varied stimulus duration within the range of 100–800 ms, keeping stimulus 1 and stimulus 2 durations ($T1$ and $T2$) equal. As $T1$ and $T2$ increase, rats' intensity-difference threshold decreases, indicating that more reliable representations emerge over time (Fassihi et al., 2020). This finding parallels the decrease in threshold with increasing duration in humans (Fassihi et al., 2020) – rats thus integrate information over time in a human-like manner.

In further experiments, we varied $T1$ and $T2$ but no longer kept them equal (Fassihi et al., 2017; Toso et al., 2021a). In the case of unequal stimulus durations, the briefer stimulus was perceived as less intense and the longer stimulus as more intense: "longer feels stronger" (Fig. 5B, left plot). Thus, with increasing vibration duration, two perceptual effects occur: (i) heightened acuity, as predicted by positing the integrator as an ideal observer, and (ii) a feeling of increased intensity. On statistical grounds, the estimate of the central tendency of an underlying distribution should become more reliable with increased sampling (mirroring the observed growth in acuity) but should not shift (unlike
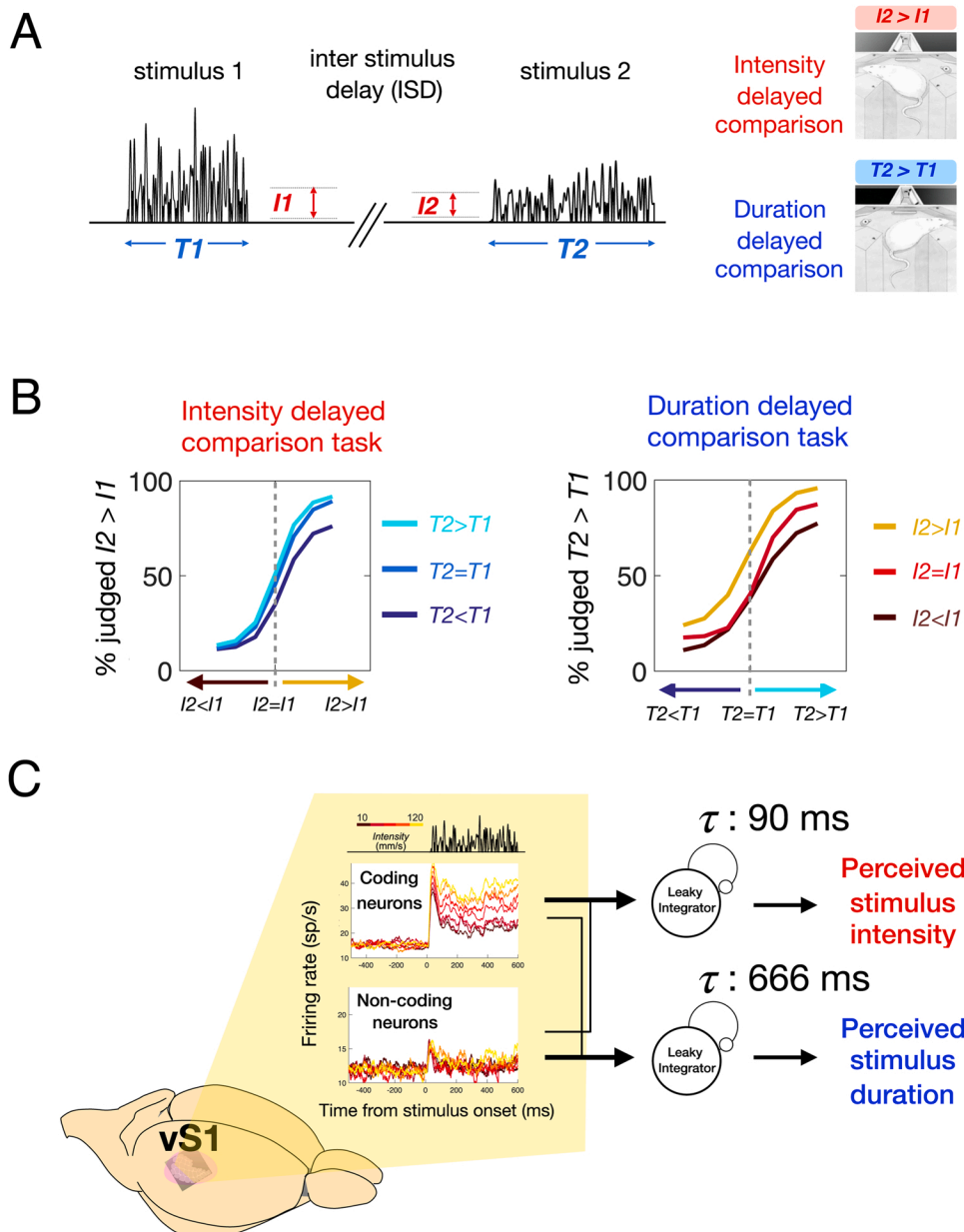
Fig. 5. Accumulation of evidence in vibration perception. (A) In a delayed comparison task, the rat is presented on each trial with two noisy vibrations separated by an interstimulus delay (ISD). The two stimuli are characterized by their intensities (*I1* and *I2*) and durations (*T1* and *T2*). After a go cue, the rat commits to a choice by selecting one of two reward spouts. (B) Left panel depicts psychometric curves obtained in the *intensity delayed comparison task*. The probability of judging stimulus 2 intensity as stronger increases both with intensity difference and the duration differences between the two stimuli: longer feels stronger. Right panel depicts the symmetrical bias obtained in the *duration delayed comparison task*: stronger feels longer. (C) Leaky integration of vS1 neuronal activity by a downstream region is posited as a neurophysiological mechanism underlying perception. Perceived stimulus intensity is generated by integration of a large portion of vS1 intensity coding-neuron and a small portion of non-intensity-coding neurons, with a short time constant (70–100 ms). Perceived stimulus duration is generated by integration of a smaller portion of vS1 intensity coding-neuron with a long time constant (300–800 ms). Based on results of (Fassihi et al., 2017) and (Toso et al., 2021a).

the observed growth in perceived intensity). The "longer feels stronger" effect is thus at odds with an ideal observer.

The *duration delayed comparison* task (Toso et al., 2021a) uncovered a symmetrical cross-talk between these two perceptual features: not only does "longer feels stronger" (*intensity*) but "stronger feels longer" (*duration*) (Fig. 5B, right plot). The major psychophysical findings from rats generalized to human subjects (Fassihi et al., 2014, 2017; Toso et al., 2021a).

The ultimate goal remains that of understanding the processing giving rise to the two percepts, intensity and duration. In vS1, both neurons whose firing rate is dependent on stimulus intensity (intensity-coding neurons) or independent from it (non-intensity coding neurons) can be found. The neuronal firing probability of the former is set by whisker motion in the preceding 5–50 ms (Fassihi et al., 2017). In other words, the presence or absence of a spike at any given instant reports only the vibration's recent kinematic features (Esmaeili and Diamond, 2019). Like the single-touch coding in the texture task, this "local" vibration code could not, by itself, account for the two percepts. In other words, vS1 firing does not constitute an explicit representation of the stimulus feature required to solve the task. In practice, the investigator, upon recording the neuronal activity therein, cannot decode the percept that guides behavior unless the measured activity is accumulated over time: additional processing is required. We refer to the post-vS1 processing as downstream integration without, for now, positing whether the downstream centers are within cortex or within subcortical structures.

A physiological mechanism akin to leaky integration (Usher and McClelland, 2001; Wang, 2002) appears to be a plausible mechanism. Neurometric curves (simulations of behavior based on a posited algorithm for converting neuronal activity to choice) mimic observed *intensity* psychophysical curves when the integrator accumulates the firing of vS1 intensity-coding neurons with a 70–100 ms time constant, $\tau_{intensity}$ (Fig. 5C). The neuronal substrate of the percept can thus be envisaged as the physiological state of a downstream neuronal population that is continuously driven from baseline by the amplitude of vS1 input and is simultaneously relaxing towards baseline, proportionally to the current state. The time constant dictates that the percept will reach steady state about 3 times τ (approximately 300 ms) after vibration onset. At steady state, the vS1 driving force and the relaxation (leakage) are in equilibrium.

In parallel, neurometric curves mimic observed *duration* psychophysical curves when the algorithm integrates the firing of vS1 with a 300–800 ms time constant, $\tau_{duration}$ (Fig. 5C). Importantly, the matching of neurometric and psychophysical curves for duration perception occurs only by positing input from a large portion of vS1 non-intensity-coding neurons. The inclusion of too many intensity-coding neurons leads to magnification of the intensity bias of the neurometric curve: stronger stimuli would be judged as having far too long a duration and weak stimuli far too short. For duration, the neuronal substrate of the percept can thus be envisaged by dynamics schematically similar to those of intensity perception but differing by physiological parameters. Because the tested stimulus durations were shorter than the interval at which the integrator would reach steady state (about 3 x $\tau_{duration}$), the percept would be modeled as growing continuously with time – a requisite for any duration percept. To afford duration perception beyond 1–2 s, either the time constant must adapt to the ongoing context or else some other circuitry must be at work.

Which downstream circuits are responsible for the integration? Although feedback to high-order thalamic nuclei, as in the visual system (Sherman, 2016), is one possibility, neuronal populations in vM1 (a frontal cortex area targeted by vS1) appear to act as temporal integrators (Fassihi et al., 2017) – their firing is modulated by both stimulus intensity and stimulus duration, paralleling the behavioral confound of stimulus duration on perceived intensity. On the other hand, the circuit at work for duration perception is yet to be found. In humans, premotor cortical regions might be involved (Protopapa et al., 2019). Because of

the existence of a gradient of integration timescales in the cortex (Murray et al., 2014), in rodents possible candidates include neural populations located anterior to vM1. The dorsal lateral striatum carries precise timing information (Gouvêa et al., 2015), but the information carried in neuronal populations seems to be more closely connected with the configuration of task-dependent actions and choices over time than with the percept itself (Toso et al., 2021b).

Much more rapid temporal integration has been proposed as the basis for other vibrotactile tasks. Rats were trained to detect pulses delivered to a single whisker when the number and the frequency of pulses varied across test trials (Stüttgen and Schwarz, 2010). Neurometric curves matched psychometric curves when vS1 neuronal activity was modelled as being integrated through a leaky integrator with $\tau < 25$ ms. Similar integration time constants are uncovered when rats compare the repetition frequency of pulsatile vibrotactile stimuli presented bilaterally to C1 whisker (Musall et al., 2014). Thus, provided that brief stimulus epochs contain all necessary information, the short integration time constant characteristic of vS1 local circuits (or even pre-cortical stages) may be sufficient to set up the explicit signal required to solve the task. This stands in contrast to the case where the task can be solved only on the basis of long streams of stimulus information (Fassihi et al., 2017; Toso et al., 2021a).

The observations made in the texture and the vibration tasks suggest a general framework for rodent tactile perceptual decision making not unlike that formulated for primate visual motion perception. Sensory evidence is accumulated up to a boundary, at which point the brain commits to a choice (Huk and Shadlen, 2005). Although there are advantages inherent to rapid decision making, choices must also be grounded in solid information, in evidence that is acquired and accumulated over time. In this integrative process, vibrissal somatosensory cortex (vS1 and vS2) do not act as the integrators, but as the distributors of sensory information to downstream regions. Still, it is unlikely that a comprehensive subjective experience, encompassing the feeling of elemental stimulus features together with the meaning with which such features have been tagged through extensive training, could be localized to a single brain region. A unifying perspective is that of reciprocating feed-forward and feedback loops which cooperate to form a distributed substrate that is experienced as a percept (Yang et al., 2015; Kwon et al., 2016). A remaining challenge is to identify the specific contributions of identifiable brain regions to identifiable components of the perceptual event.

7. Pattern recognition

Like the overall intensity within a stochastic stream of motion (see above), a pattern played out over time cannot be identified by instantaneous elements within the sequence. A task was recently developed (Fig. 6) in which mice had to recognize a continuous modulated noise sequence delivered to whiskers, defined by its temporal patterning over hundreds of milliseconds (Bale et al., 2017, 2021). GO and NO-GO sequences differed only in that the order of their constituent noise modulation segments was temporally scrambled. Mice efficiently learned tactile sequences, showing results qualitatively similar to those of human subjects. They could respond to the earliest possible cues allowing discrimination, effectively solving the task as a "detection of change" problem, but enhanced their performance when responding later. Optogenetic inactivation of vS1 and vS2 decreased sequence discrimination, suggesting a participation of these two regions in the task (Bale et al., 2021). However, as remarked earlier, transient inactivation effects are not, by itself, proof of a causal role of the manipulated brain region (Otchy et al., 2015). Interestingly, two-photon imaging in layer 2/3 of vS1 gave evidence supporting a role of vS1 in the animal's learned action in response to the target sequence, although it is not clear whether such decision-related activity reflects a causal contribution of vS1 to choice or else a post-choice feedback to vS1. In recent work, similar decision-related activity in a vS1 subpopulation was shown to
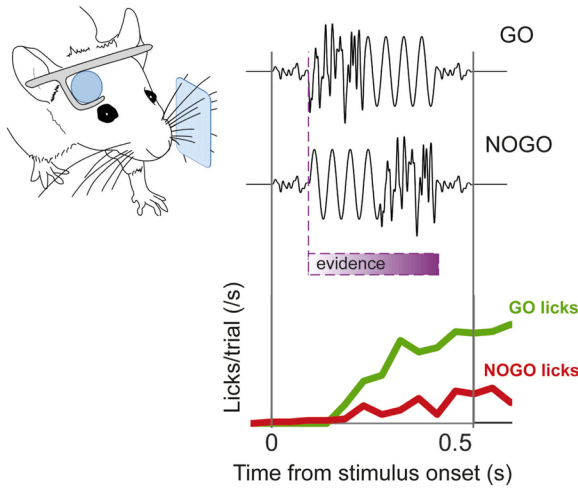
Fig. 6. Pattern recognition. The mouse receives patterned motion through its whiskers, fixed in a mesh. One motion sequence (low-amplitude noise, high-amplitude noise, sinusoid, low-amplitude noise) is a GO pattern, while the other (low-amplitude noise, sinusoid, high-amplitude noise, low-amplitude noise) is a NOGO pattern. Evidence for one or the other pattern grows from the moment they first diverge (represented by increasing colour gradient of purple bar). Below, the performance of an expert in an example session is shown: the mouse licks more to GO than to NOGO, beginning a few hundred ms after the point where the two stimuli first begin to diverge. Figure kindly provided by M. Maravall (Bale et al., 2017, 2021).

have a direct casual contribution on animal's behavior through opto-genetic activation (Buetfering et al., 2022).

8. The current percept within its recent context

In a sensory-perceptual paradigm known as "reference memory," the subject gains rewards by correctly identifying each stimulus in relation to a fixed boundary (the reference). Individual stimuli are characterized by their value along some scaled dimension. In reference memory of vibration intensity, each vibrissal stimulus must be categorized as stronger or weaker than the designated boundary (Fig. 7A). While individual vibrations are exactly of the form described in Section 6, the key difference is that the comparison is not made to the neighboring stimulus but, ideally, to the fixed reference. Stimuli are presented sequentially in a long session. This paradigm reveals that the generation of a percept does not derive exclusively from the incoming sensory input, but also from the incorporation of a prior history of stimuli.

How does the current perceptual choice depend on trial history? Intuition tells us that the brain must generate, hold, and apply an internal criterion. For optimal performance in a laboratory setting, the brain's decision criterion would be identical to the reward rule imposed by the experimenter, that is, the boundary that separates the two stimulus categories. Recent studies, however, suggest that the task might be accomplished without any abstract conception of a boundary, per se – it appears that the "reference" consists of a stored and continuously updated representation of the string of preceding stimuli (Hachen et al., 2021; Yousefi Darani et al., 2023). The main empirical result is that after a low-intensity stimulus (trial *n-1*), rats are more likely to report the next stimulus (trial *n*) as strong; after a high-intensity stimulus (*n-1*), they are more likely to report the next stimulus (*n*) as weak (Fig. 7B). This "repulsive" influence of preceding stimuli endures substantially longer than the time scale of low-level sensory adaptation (Maravall et al., 2013). Indeed, the effect can be tracked over several preceding trials, extending as far back as *n-6*. This same effect has been replicated in humans in the same psychophysical task, implying a species-general mechanism (Hachen et al., 2021).

Because the behavioral task is self-paced by the rat, there is considerable spread within the inter-trial interval (ITI) distribution (from stimulus-to-stimulus, measured in seconds). Separating the trial *n* psychometric curves according to preceding ITI reveals that after a long ITI (e.g., 12 s) *n-1* exerts a stronger effect on trial *n* judgment than after a

Fig. 7. Building the current percept in its sensory context. (A) In the reference memory task, the rat is presented on each trial with one noisy vibration (left). The rat selects one of two reward spouts according to the difference between stimulus intensity and a fixed boundary (right). (B) The probability of judging stimulus *n* as "strong" is biased by stimulus *n-1* intensity. After a weak stimulus rats are more likely to report the next stimulus as strong (light grey), and vice-versa (black). (C) The rat's behavior can be successfully modeled by assuming that the decision criterion (in black) and stimulus memory trace (in brown) mutually attract each other during the course of each Inter-trial interval (ITI). Thus, the decision criterion is continuously updated. The time constant, *t*, characterizes the strength of attraction. Based on results of (Hachen et al., 2021).

short ITI (e.g., 5 s), signifying that stimulus *n-1* does not exert its effect in a single step but as a continuous function. Like the many-trial history alluded to above (as far back as *n-6*), the gradually increasing influence of *n-1* argues against low-level adaptation; an adaptation effect would vanish as ITI grows.

The judgment of vibration intensity can be captured by assuming that the brain's decision criterion for separating weak from strong is comprised of one representation, while the most recent stimulus intensity memory trace is comprised of a second representation, and these two mutually attract each other over time (Fig. 7C). Although the memory trace of the most recent stimulus is not intentionally used in the reference memory task, the significance of its attraction towards the decision criterion will become evident when we discuss other memory tasks. Thus, the dynamic updating of decision criterion, *μ(t)*, can be modeled by the expression:

$$\mu(t) = \mu(t_0) \cdot e^{\left(-t/\tau\right)} + stimulus\ n-1_{trace}(t) \cdot (1 - e^{\left(-t/\tau\right)}) \tag{1}$$

where *μ(t₀)* is the decision criterion at the presentation of stimulus *n-1* (equivalent to *μ_{n-1}*), *t* is the elapsed time after presentation of stimulus *n-1*, and *stimulus n-1_{trace}(t)* is the stimulus *n-1* memory trace. At $t = t_0$, the stimulus *n-1* memory trace is a faithful representation of the just-delivered stimulus.

Symmetrically, the convergence of *stimulus n-1_{trace}(t)* towards *μ(t)* can be expressed as:

$$stimulus\ \ n-1_{trace}(t) = stimulus\ \ n-1_{trace}(t_0) \cdot e^{\left(-t/\tau\right)} + \mu(t) \cdot (1 - e^{\left(-t/\tau\right)}) \tag{2}$$

where, again, *stimulus n-1_{trace}(t₀)* is equivalent to stimulus *n-1* intensity. In both equations *τ* is a time constant that determines how rapidly *μ(t)* is drawn to the memory trace of the most recent stimulus and, simultaneously, how rapidly the memory trace of the most recent stimulus is drawn to *μ(t)*. The rat's decision is posited to result from comparing the real time sensory representation of stimulus *n* to the criterion *μ_t* at the moment of stimulus delivery, whose value is determined by the time elapsed since delivery of stimulus *n-1*.

This model for the decision criterion has only a single free parameter, *τ*. From Eqs. 1–2, the dynamics at work in a given rat's brain can be uncovered by simulating the trial-by-trial criterion that would result from a selected value of *τ* and comparing the predicted choices (is stimulus *n* stronger or weaker than simulated *μ(t)* at the moment of vibration?) to the rat's observed choice. Testing a range of *τ* values allows one to uncover the time constant best matching the actual rat behavior by minimizing the error between predicted and observed choices (Hachen et al., 2021; Yousefi Darani et al., 2023). There is significant variability across rats' time constants, ranging from about 10–60 s. A longer *τ*, implying a more stable choice criterion, is adaptive provided that the reward rule imposed by the experimenter is stable. Interestingly, longer *τ* correlates with better performance. It remains to be determined where in the brain, and how, the prior distribution of stimuli is built and stored.

9. Linking tactile percepts across time: Delayed comparison

Experiencing a smooth flow of events requires the existence of a short-term perceptual memory buffer, a stored representation of preceding sensory events to which the current sensory input is continually connected, linked, and compared. If a rat perched along the subway tracks were to collect vibrations transmitted through the rails to compute the direction of a train, a vibration sequence of growing versus diminishing amplitude would have opposite causes (approaching versus moving away, respectively). Solving this task is an ecological version of working memory: is the current vibration weaker or stronger than the preceding one? Tactile cognition, in other words, entails storing

percepts and making them available for future comparisons, choices, or actions.

In Section 6, delayed comparison experiments (Fig. 5A) were analyzed to discern the integration of information within the course of one stimulus. The same studies (Fassihi et al., 2014) can also provide insights into the storage of information across the interstimulus delay (ISD). In this paradigm, rats can hold stimulus 1 information for up to 8 s (the longest ISD tested), thus rivaling human performance (Fig. 8A).

vS1 robustly represents the stimulus in real time, with the firing rate of about 40–60% of neurons encoding vibration intensity (in units of mean speed, mm/s) in a graded manner (Fassihi et al., 2017; Esmaeili and Diamond, 2019). If we take persistent firing to be one measure of information storage, in vS1 the degree of stimulus 1 retention (the proportion of stimulus-encoding neurons that continue to carry signals) is about 10–20% by the end of a 2-second delay. The firing of regions of frontal cortex is particularly well suited to a role in bridging from stimulus 1 to 2 . While less strongly engaged in real time coding, neurons in vibrissal motor cortex (vM1) and prelimbic cortex (PL) show a higher degree of retention: about 40% of those neurons with real time signals still hold a robust memory trace in their firing by the end of the 2-second delay. The results summarized above correspond to trials which culminate in a correct choice; on incorrect trials, real time coding and memory is degraded throughout sensory cortex and frontal cortex, confirming their firing as a substrate for the behavior.

Psychometric analysis shows that as the ISD extends, stimulus 1 tends to be remembered as progressively closer to the expected value of the session's entire stimulus distribution. In other words, a very weak stimulus 1 will be remembered, at the time of comparison, as stronger than it actually was whereas a strong stimulus 1 will be remembered as weaker than it actually was (Fig. 8B; see (Fassihi et al., 2014; Toso et al., 2021a)). Since sensory memories seem to "contract" towards some sort of prior, this memory distortion is known as contraction bias (Hollingworth, 1910; Ashourian and Loewenstein, 2011) and is general to all sensory modalities (Levy et al., 2015).

In the formulation of reference memory in the preceding section (Eqs. 1 and 2), the quantity referred to as the memory trace of the most recent stimulus, *stimulus n-1_{trace}(t)*, might offer an inroad to understanding contraction bias. While the most recent stimulus (*n-1*) is not explicitly used to solve the reference memory task, it is essential to the delayed comparison task. The properties of *stimulus n-1_{trace}(t)* would make it suitable to represent the working memory of stimulus 1. In Eq. 2, the memory trace of stimulus *n-1* is gradually attracted to *μ(t)*, a longer-term buffer whose contents are the weighted mean of the string of preceding stimuli. While in reference memory tasks we argue that *μ(t)* serves as the brain's criterion for judging the intensity of each new stimulus, in delayed comparison tasks the very same memory buffer could work as an attractor of the stimulus 1 memory, thus explaining the phenomenon of contraction bias (Fig. 8C). As ongoing research builds on the evidence for frontal cortical involvement in holding the memory trace of stimulus *n-1* (Fassihi et al., 2017; Esmaeili and Diamond, 2019) there are indications that posterior parietal cortex (PPC) might be involved in contraction bias. In rats performing a delayed comparison task, optogenetic inhibition of PPC neuronal activity reduces the effects of prior sensory stimuli on the base stimulus (stimulus *n-1*) memory, presumably by interruption the attraction of the working memory towards the longer-term prior (Akrami et al., 2018). Although the study involved delayed comparison of acoustic stimuli, the results likely generalize to touch.

10. Linking stimulus to action: Delayed response

A key aspect of decision making is not only the use of sensory information to select action, but also the ability to execute the action at the safest moment. In delayed response tasks, an interval is inserted between the sensory event and the go cue that "releases" the chosen action. In non-human primates, neurons exhibiting preparatory activity during the
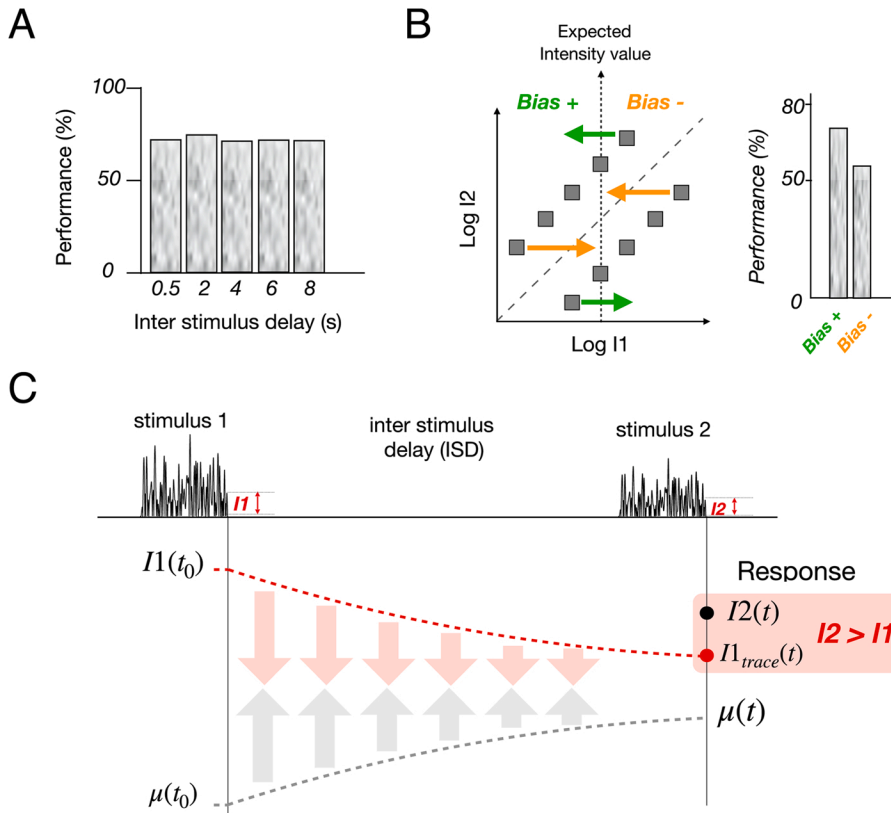
Fig. 8. Bridging tactile percepts across time: delayed comparison. (A) In delayed comparison tasks, rats can hold stimulus 1 information across an interstimulus delay (ISD) lasting up to 8 s. The results are based on stimulus pairs less subject to contraction bias. (B) Each square in the left panel depicts a *I1/I2* pair presented to the animal in an *intensity delayed comparison task*. The memory of stimulus 1 is contracted toward the expected value of the recent stimulus distribution. According to whether the contraction is towards or away from the diagonal (dashed line), this contraction bias can either make a stimulus pair easier (bias +, in green) or harder (bias -, in orange) to compare. Right panel shows how performance is shaped by contraction bias in the selected pairs. (C) Contraction biases can be computationally formulated as arising from the mutual attraction of stimulus 1 intensity memory trace ($I1_{trace}(t)$, red dashed line) and the long-term memory buffer $\mu(t)$ (black dashed line) along the course of the ISD. In this example trial, the downward contraction of $I1_{trace}(t)$ towards $\mu(t)$ leads to the erroneous classification of *I2* as being stronger than *I1*. Panels A and B based on results from (Fassihi et al., 2014) and (Toso et al., 2021a); model of panel C based on (Hachen et al., 2021).

delay period have been found in premotor and supplementary motor areas (Alexander and Crutcher, 1990). Mice can be trained to discriminate the location of an object in one of two positions during a sampling epoch (the tactile input) and must report object location by licking at one of two ports, but only after a delay (Fig. 9A) (Chen et al., 2017). Preparatory activity selective to the upcoming action (Fig. 9B) can be found in the deep layers of anterior lateral motor cortex (ALM) in the time preceding the go cue. The ALM is connected bidirectionally with several ipsilateral thalamic nuclei, including ventro-medial and ventro-anterior-lateral nuclei. As in ALM, preparatory activity is found in these thalamic neurons (Guo et al., 2017). Moreover, when the thalamus is optogenetically inhibited during the delay epoch, ALM preparatory activity is abolished, indicating that thalamo-cortical reciprocating loops are needed to support the behavior. ALM preparatory activity has been shown to be robust to transient perturbations (Li et al., 2016). When optogenetic inhibition is applied unilaterally to ALM, the preparatory activity is transiently abolished but recovers rapidly after inhibition offset, while it is strongly impaired both when bilateral ALM inhibition is applied and when ALM corpus callosum is bisected.

Recent work in mice indicates that under some conditions a small neuronal population in vS1 expresses categorical texture information and retains that information in a delay prior to the lick-response (Buetfering et al., 2022). Interestingly, the decision signal encoded by this vS1 subpopulation developed with learning of the task. Moreover, optogenetic stimulation of "decision-neurons" increased animals' behavioral performance, indicating a causal contribution of the subpopulation on mice behavior. Overall, these results indicate that the ability to prepare and execute an action after a delayed time involves a redundant and modular network, which includes bilateral ALM and their thalamo-cortical connections and even vS1. A limitation to such studies is that they do not specify whether the persistent post-stimulus neuronal firing corresponds to a memory of the stimulus, a prospective preparation of upcoming action, or both.

11. Bridging between touch and other modalities

Once we are familiar with the combined sensory properties of an object, we can recognize that object independently of the modality by which we receive the sensory signal – a banana, for instance, is the same fruit by sight, by texture and shape, by taste. One form of tactile cognition is the use of touch to activate the supramodal representation of an object. In an experiment designed to explore the involvement of the rat cerebral cortex in recognizing an object through both touch and vision (Nikbakht et al., 2018), we trained rats to judge the orientation of a circular object, of 10 cm diameter, composed of raised parallel bars alternately colored white and black (Fig. 10A). Object orientation was reset by a rotating motor on each trial. When presented with an orientation in the horizontal category – a range of 0 +/- 45 degrees, the rat could get a juice reward by licking the left spout; presented with an orientation in the vertical category – a range of 90 +/- 45 degrees, the rat could get a juice reward by licking the right spout (Fig. 10B). On each trial, a set of computer-controlled transparent panels and light-emitting diodes allowed the rat to explore the grating through the visual modality alone (V), using its whiskers in the tactile modality alone (T), or both visual and tactile modalities together (VT). The performance of the rat in judging orientation was measured by psychophysical performance curves. The curves plot the proportion, across many thousands of trials, in which the rat judged the orientation as vertical when they encountered the object in the tactile, visual, and combined visual-tactile modalities, respectively. As seen in the plots generated by averaging across all rats (Fig. 10C), the visual and tactile modalities alone supported similar levels of performance, but the two modalities seem to be integrated to provide much better orientation judgment on VT trials.

Where in the brain do the two distinct sensory channels "work together"? PPC (the same region involved in the working memory contraction bias), designated in light red in Fig. 10D, is situated between the somatosensory cortex input (vS1 barrels and vS2 are shown in green) and the visual area (blue) and is a target of projections from both (Akers

A

sample   delay   response

1.3 s   1.3 s

B

Ipsilateral   *Contralateral*

ALM   ALM

Thal.

ALM

Delay

Ipsi. Choices
Contra. Choices

Firing rate (sp/s)

Time (s)

Thalamus (VM/VAM)

Ipsi. Choices
Contra. Choices

Firing rate (sp/s)

Time (s)
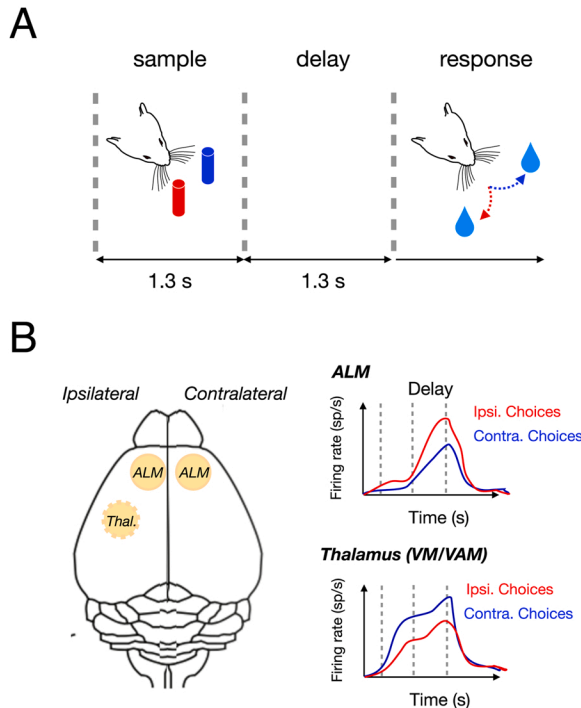
Fig. 9. Bridging from stimulus to action: Delayed response. (A) Mice judge the location of an object through their whiskers during a sampling period. They maintain the memory of the location, or the choice, for a 1.3 delay epoch, during which they plan the upcoming choice. After an auditory go cue animals report the object location through bidirectional licking. (B) Preparation and execution of action involves a modular network including bilateral ALM and ipsilateral ventro-medial (VM) and ventro-anterior-lateral (VAL) nuclei (left panel). During the delay period neurons in ALM and thalamic nuclei (subcortical position indicated by dashed line) show selectivity for the upcoming choice in their firing rate. Based on results from (Guo et al., 2014).

and Killackey, 1978). Responses of two example neurons in posterior parietal cortex are shown in Fig. 10E. For the neuron in the upper panel, firing rate varied smoothly in relation to the angle of the stimulus. For the neuron in the lower panel, firing rate differed sharply according to whether the stimulus was in the horizontal (0–45 degrees) or the vertical category (45–90 degrees); firing did not vary in relation to angles within a category. All the examined neurons in PPC, whether they encoded object angle by a graded code or else object category by a step-like code, did so independently of the sensory channel(s) through which the rat encountered the object. The cortical circuit that could produce modality-independent responses is shown schematically in Fig. 10F, where purely visual (blue) and purely tactile (green) neurons converge upon a population (red) which combines the modalities. The convergence means that both modalities activated the same supramodal representation of the object, as opposed to the two modalities conjuring up two separate representations. However, this modality-free coding in PPC was not found in other multisensory decision-making task, in which auditory and visual pulses had to be integrated by rats (Raposo et al., 2014). We hypothesize that supramodal coding in the orientation task is a consequence of the nearly simultaneous arrival in PPC of congruous signals, through two sensory channels, about a real object. Coherence between modalities, as in our study, might better reflect the statistics of the real world. A rodent might need to maneuver through oriented bars (a storm drain along the street), whether those bars are seen or felt. The modality-invariant object recognition shown by rats can provide candidate mechanisms for the human brain's capacity to call up knowledge about things independently of sensory input channel (Quiroga et al., 2005).

To prove a causal role of PPC in multisensory decision-making tasks,

optogenetic manipulation in behaving animals would be needed. Recent work lead to conflicting results, revealing an involvement of parietal cortex in multimodal audio-visual perceptual behavior in some tasks (Song et al., 2017) and not in others (Raposo et al., 2014), likely reflecting structural differences in the tasks.

12. Translational implications of tactile cognition in rodents

Abnormal tactile processing in humans is implicated in multiple neuropsychiatric disorders. Both individuals affected by Autism Spectrum Disorder (ASD) and Attention-Deficit/Hyperactivity disorder (ADHD) show atypical tactile perception in a variety of tasks such as detection threshold, amplitude discrimination and frequency discrimination (Puts et al., 2014; Robertson and Baron-Cohen, 2017; He et al., 2021). Specific genetic diseases, such as Rett syndrome and Fragile X syndrome, are commonly associated with ASD and express similar tactile perceptual abnormalities (Rogers et al., 2003).

Animal models of such diseases are an opportunity for understanding the physiological basis of normative and pathological human neurological function, including the alterations in tactile perception outlined above. If sensory processing alterations are one local manifestation of a more generalized nervous system dysfunction, then insights from rodent tactile studies could facilitate a deeper understanding of the underlying human neuropsychiatric disorder (Kaiser et al., 2017). For example, four different mouse models of ASD exhibit altered tactile discrimination performance, which was found to be linked to mechanosensory dysfunction at the level of peripheral neurons (Orefice et al., 2016). Mouse models of Fragile X syndrome (Fmr1-KO) exhibit circuit dysfunctions at the cortical level, with altered excitability and spike timing of barrel cortex neurons in response to thalamocortical input (Domanski et al., 2019) and to repetitive whisker stimuli (Juczewski et al., 2016). When tested in the gap-crossing task (Fig. 3 of the present review), Fmr1-KO mice were able to gap cross but applied fewer whisker contacts, as if hypersensitive to touch (Juczewski et al., 2016).

Other findings about clinically altered tactile processing were reported in a genetic neurodevelopmental disorder linked to Syngap1 haploinsufficiency. Individuals affected by this clinical condition show cognitive impairment, autistic features, and epilepsy (Agarwal et al., 2019), as well as tactile-related sensory impairments (Michaelson et al., 2018). Interestingly, in the Syngap1 mouse model of the disease neurons show impaired excitability and reduced synaptic connectivity at the level of primary somatosensory cortex (Michaelson et al., 2018).

Non-normative tactile processing has been seen in individuals affected by Schizophrenia. While in healthy subjects self-generated tactile stimuli are perceived as less intense compared to externally delivered one (Bays et al., 2005), such attenuation does not occurs in schizophrenic patients (Shergill et al., 2005). Animal models of schizophrenia (Johnstone et al., 2011) may be an important tool to better understand these alterations.

13. Conclusions

Our synthesis makes a distinction between tactile cognition versus behaviors explained as acting on pure tactile sensory data. Extending from the concepts proposed in other modalities and reviewed by Whitfield (Whitfield, 1979), we suggest that action initiation networks can be engaged through pre-cortical sensory representations provided the information necessary for the choice is explicitly encoded there. Typically, this involves brief events (deflections, instantaneous changes in stimulus features), analogous to the acoustic interaural time difference (Masterton and Diamond, 1964). We speculate that what pre-cortical processing cannot accomplish are the operations of linking and integrating – linking between stimuli across time (e.g. delayed comparison), integrating a statistically complex stimulus over time (e.g. vibration or texture), linking between touch and other modalities (e.g. visual-tactile orientation identification), linking in time from sensory input to choice. Gap
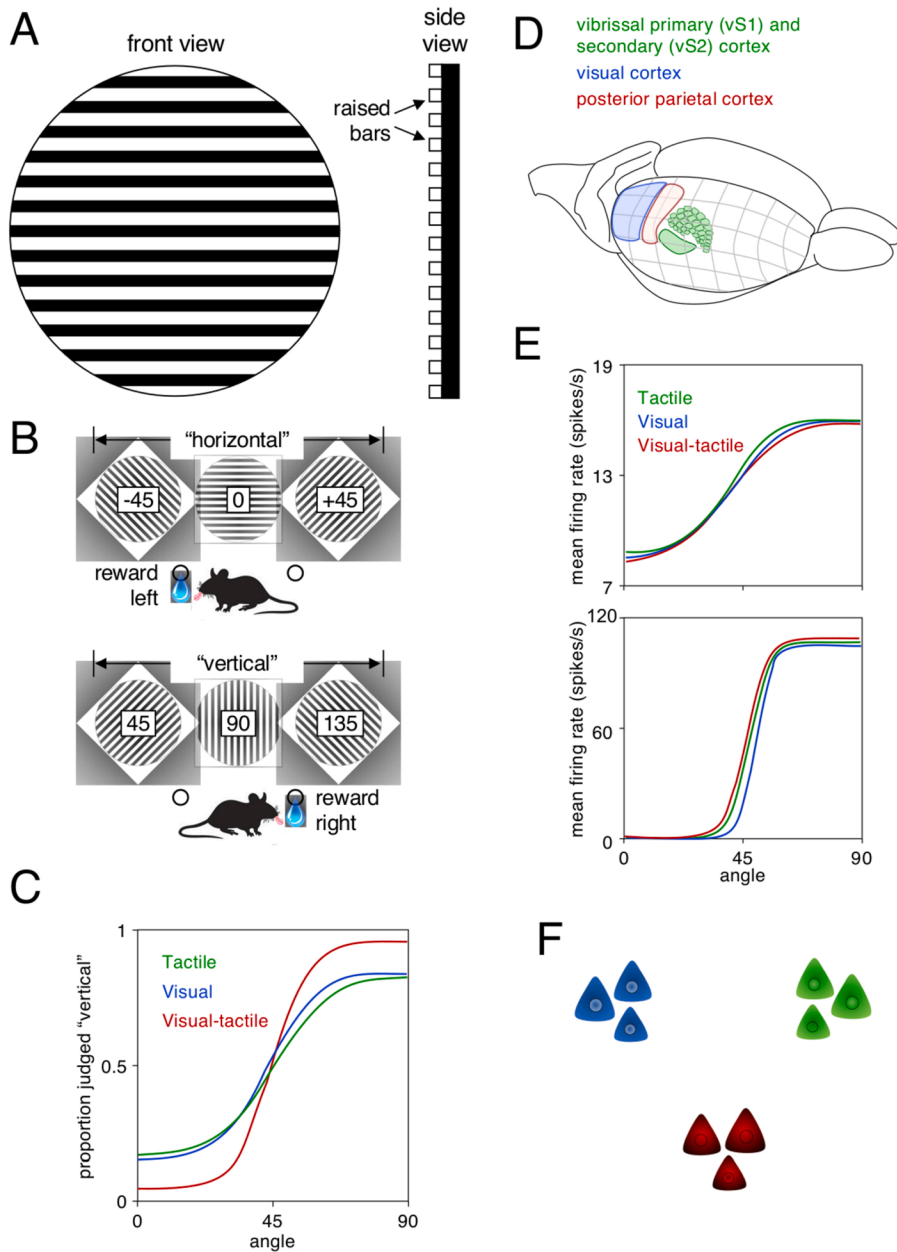
Fig. 10. Generation of a supramodal representation. (A) The stimulus was a disk formed of white bars raised against a black background. (B) The disk assumed an orientation on every trial between − 45 and 45 degrees, categorized as horizontal, or between 45 and 135 degrees, categorized as vertical. Reward location depended on orientation. (C) Average performance of all rats on trials under three sensory conditions. In this and in successive panels, data from 90 to 135 degrees and from − 45–0 degrees are "folded back" around the edges, 90 and 0 degrees, respectively. (D) Position of posterior parietal cortex (PPC), interposed between visual cortex and vS1 and vS2. (E) PPC neurons with a graded (upper panel) and categorical (lower panel) response to object orientation. Firing rates were equivalent across the three sensory modalities. (F) Schematic depiction of the generation of supramodal (red) representations by the convergence of unimodal visual (blue) and tactile (green) representations. All panels based on (Nikbakht et al., 2018). In panels C and E, error bars visible in the original publication are omitted for clarity.

crossing, too, can be conceived of as linking the current sensory input to stored representations – as the forward-thrust whiskers collide with a surface (Fig. 3), the whisker kinematics encoded in the ascending sensory pathway evoke (provided cortical processing is intact) the rat's remembered mental representation of the platform.

Beyond the direct cortical involvement in tactile cognition highlighted in this review, it is important to acknowledge that non-cortical areas such as cerebellum (Proville et al., 2014) or striatum (Alloway et al., 2017) might be involved in tactile cognition as well, by virtue of their cortical connectivity. Moreover, as pointed out in previous work (Stüttgen and Schwarz, 2018), apart from permanent lesion studies (Hutson and Masterton, 1986), it is hard to draw an unequivocal proof of cortical involvement from correlative or manipulative studies only.

When you hear your cell phone ringing from somewhere deep in your knapsack, you must navigate among the sack's many items to identify the phone by touch. As you do so, you will not operate according to a mental representation of your fingertips and the various vibrations, punctate pressures, and translations transmitted through them. Rather, your mental representation will be of the keys, the wallet and, finally, the searched-for cell phone. That is so even if keys, wallet, and phone could not be mentally evoked if not for the sensory data of the fingertips. When a rodent feels for nesting materials (Rhodes and Richmond, 1985), one can imagine an analogous evoking of representations of real things triggered by data streams from the sensory receptors. Our contention, in broadest strokes, is that the computations that take place in the cerebral cortex, beginning with primary sensory cortical representations as the raw material, are the basis for tactile cognition.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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