New perspectives on the neurophysiology of primate amygdala emerging from the study of naturalistic social behaviors

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A major challenge of primate neurophysiology, particularly in the domain of social neuroscience, is to adopt more natural behaviors without compromising the ability to relate patterns of neural activity to specific actions or sensory inputs. Traditional approaches have identified neural activity patterns in the amygdala in response to simplified versions of social stimuli such as static images of faces. As a departure from this reduced approach, single images of faces were replaced with arrays of images or videos of conspecifics. These stimuli elicited more natural behaviors and new types of neural responses: (1) attention-gated responses to faces, (2) selective responses to eye contact, and (3) selective responses to touch and somatosensory feedback during the production of facial expressions. An additional advance toward more natural social behaviors in the laboratory was the implementation of dyadic social interactions. Under these conditions, neurons encoded similarly rewards that monkeys delivered to self and to their social partner. These findings reinforce the value of bringing natural, ethologically valid, behavioral tasks under neurophysiological scrutiny. © 2017 Wiley Periodicals, Inc.

INTRODUCTION

Despite the recent diversification of experimental subdisciplines in systems neuroscience, behavioral neurophysiology remains a staple approach to identify patterns of neural activity related to specific behaviors. Typically, behavioral neurophysiologists have reduced stimuli and behaviors to their basic elements. The main reason for simplifying stimuli or behaviors, from an experimental perspective, is to reduce the number of variables one needs to take into account. Consider, for example, attempts to understand information encoded by the activities of motor cortical neurons. At one extreme, one could record motor cortical activity in freely moving animals. While naturalistic, the number of movement variables that one would need to account for would make attempts to understand neural encoding impractical. At the other extreme, one could constrain the animal to move a single joint. In this situation, one can relate changes in neural activity to specific and measurable aspects of the behavior. However, such an approach may fail to identify the building blocks of more complex, natural movements.

While reductionist approaches have delivered major discoveries in systems neuroscience, they often failed to identify the rules governing more complex

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behaviors or the processing of natural stimuli. For example, neurons in the primary visual cortex that respond to bars of light presented at particular areas of the visual field show substantially different responses when the same bars of light, presented in the same location, are surrounded by other visual elements or embedded into a natural image.[1–5] Moreover, when subjects are allowed to freely view stimuli, this difference is even more striking.[6] Many similar observations suggest that under less restricted behavioral conditions, or in response to more complex stimuli, predictions derived from reductionist approaches are not always fully confirmed.[4,6,7]

The challenge of behavioral neurophysiology is to adopt more naturalistic behavioral paradigms but retain the ability to assign patterns of neural activity to unique changes in the external and internal environment. There is an ever-growing recognition that neuroscience would benefit from deeper understanding of behavior.[8] Part of the effort to reinstate the primacy of behavior in neurophysiology is to adopt more naturalistic and ethologically valid behavioral paradigms in the laboratory. This review focuses on new types of neural activity observed in the primate amygdala in response to more naturalistic stimuli and behaviors.

Imbedding Face Stimuli in Visual Scenes Revealed the Role of Attention in Face Processing

One component of the social brain is the distributed network of neurons specialized for face processing (face cells). These cells are clustered in cortical patches in temporal and frontal areas[9–21] and in the amygdala.[22–28] The network of cortical and subcortical face cells presumably supports the perception and discrimination of individual faces and perhaps of facial expressions.

The properties of face cells in the amygdala have been established based on their responses to static images of single faces presented on a blank background. In the monkey amygdala, face cells showed large increases or decreases in firing rate starting from 110 to 140 milliseconds after stimulus onset.[22,27] Despite evidence that eye movements modulate visual processing, the eye movements used to scan the static faces did not appear to alter the activity of face cells. This might have been an artifact of the unnaturalness of the face stimuli used in these experiments. Under natural conditions, multiple objects and faces crowd our visual field and the eye movements typically select from the scene the most salient visual details.

To determine whether eye movements during scanning of more complex visual scenes modulate the activity of face cells, we recorded neuronal responses in the human and monkey amygdala during the presentation of arrays of images that contained both faces and nonface objects (Figure 1).[29] A typical array contained two human faces, two monkey faces, and four objects such as cars, fruits, flowers, and fractals. The images were arranged in a circular array surrounding a central fixation point. After fixating on the point displayed at the center of a monitor, the array of images appeared and the subject (human or monkey) was allowed to freely scan it. Under these conditions, face-selective responses in both humans and monkeys were observed only when the subject actively allocated attention to faces by fixating their eyes on a particular face in the array.[29] These fixation target-dependent responses were most likely an effect of attention. This was confirmed by follow-up experiments in humans when covert attention (shifting attention without eye movements) produced the same effects. Furthermore, in both species, face cells showed shorter response latencies for conspecific faces suggesting that this latency advantage in the amygdala is the result of the higher social significance attributed to conspecific faces.

Similar attention-gated visual processing has been previously described in visual areas in the temporal cortex.[30] In the amygdala, this phenomenon might serve the allocation of attention to the items of high social and emotional significance within a complex visual scene. For example, the eyes are the most explored feature in a face, presumably because of the importance of the social signals they convey. Humans or nonhuman primates with amygdala lesions fail to allocate attention to the eyes in both static images and during real-life social interactions.[31–33] These results brought back into focus the mechanistically unresolved but well-documented link between attention and emotion and in the amygdala.[34]

Replacement of Static Images with Videos Provokes Natural Social Behaviors

Motivated by desire to study neural processes in response to more natural social stimuli, several laboratories have replaced static images with videos[21,26,35–44] and reported findings related to the dynamic component of these stimuli. We found that, unlike static images, videos of social displays elicited in viewer monkey's gaze-following, a reflexive reorientation of attention in the direction in
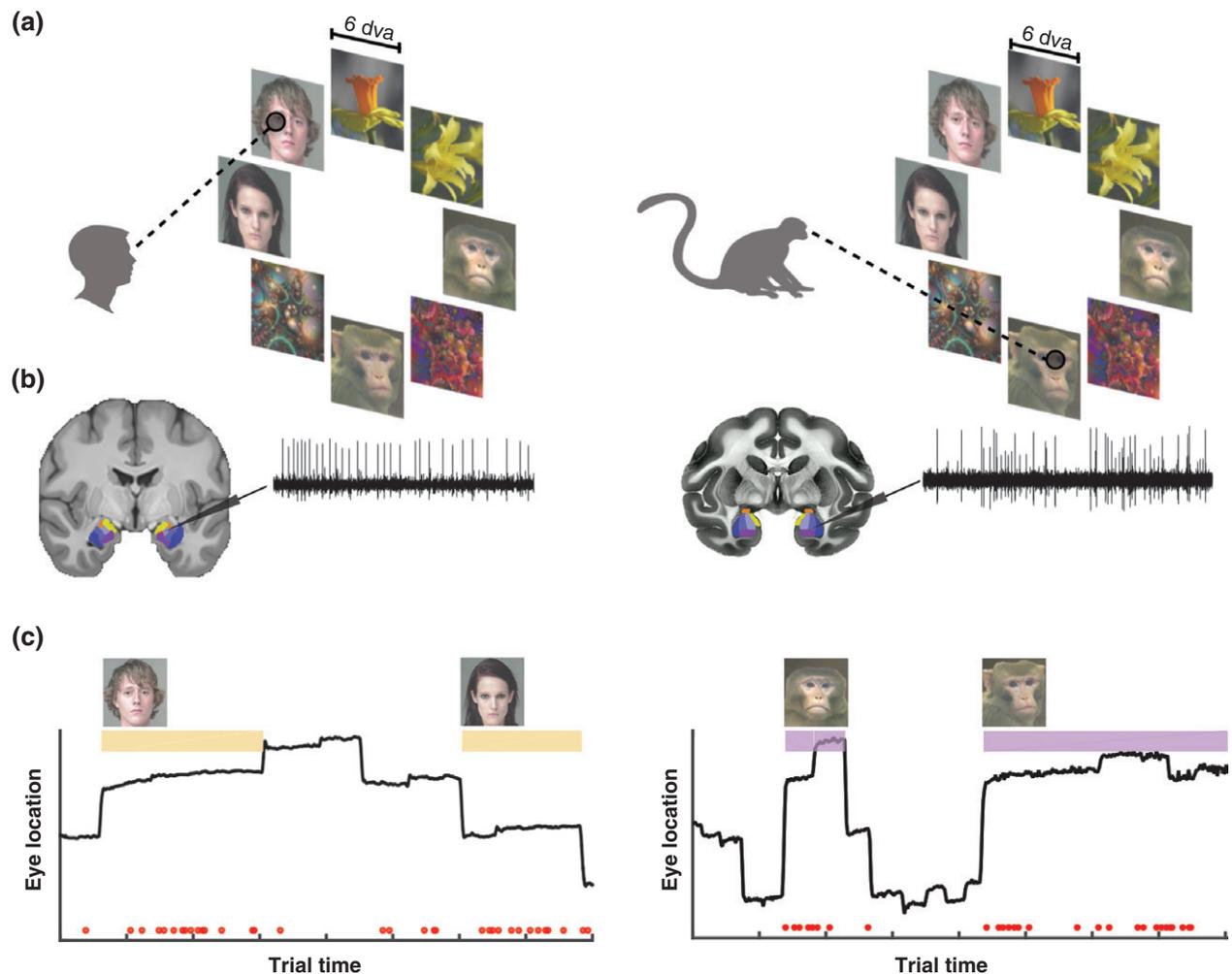
FIGURE 1 | Fixation-aligned face cell activity in the human and monkey amygdala. (a) An example stimulus array that was used for neural recordings in humans and monkeys. The dotted line indicates the image that was fixated first. Note that each species fixated first on a conspecific face. (b) Cross sections through the human and monkey brain [obtained from Magnetic resonance imaging (MRI)] indicating in the component nuclei of the amygdala in different colors. To the right of these images are representative segments of raw neural recordings. Every thin vertical line is an action potential fired by a neuron. (c) The continuous black lines indicate the vertical eye movements of the subjects. The quasi-horizontal and vertical segments of the solid black line correspond to fixations and saccades, respectively. The yellow and purple bars correspond to fixations on one or multiple faces that are shown above. The action potentials generated during these recordings are indicated by red dots at the bottom of the graph. Note the higher spike density during fixations on faces. These data show that face-selective activity in both the human and monkey amygdala is gated by fixations, the behavioral instantiations of visual attention. (Reprinted with permission from Ref 29. Copyright 2017 Cell Press 2017)

which a social partner is looking.[45,46] Static images rarely induce such spontaneous and interactive behaviors.

Furthermore, videos of conspecifics elicited in viewer monkeys the production of different facial expressions (Figure 2). Affiliative facial expressions, such as bared-teeth displays and lipsmacks, were most often observed. Lipsmacks are quintessentially dynamic facial expressions often displayed by monkeys during grooming, friendly approach, or used as signals of nonhostility or subordination.[47] During lipsmacks, the displaying individual often makes eye contact with the receiver. In the laboratory, the longer the eye contact between the viewer monkey and the monkey in the video, the more likely the viewer would produce lipsmacks.[45] This eye contact-induced social behavior has not been observed in response to static images.

Eye contact often punctuates social coordination. We also observed eyeblink entrainment induced by the videos. Viewer monkeys often blink within 500 milliseconds after they see the monkeys in the
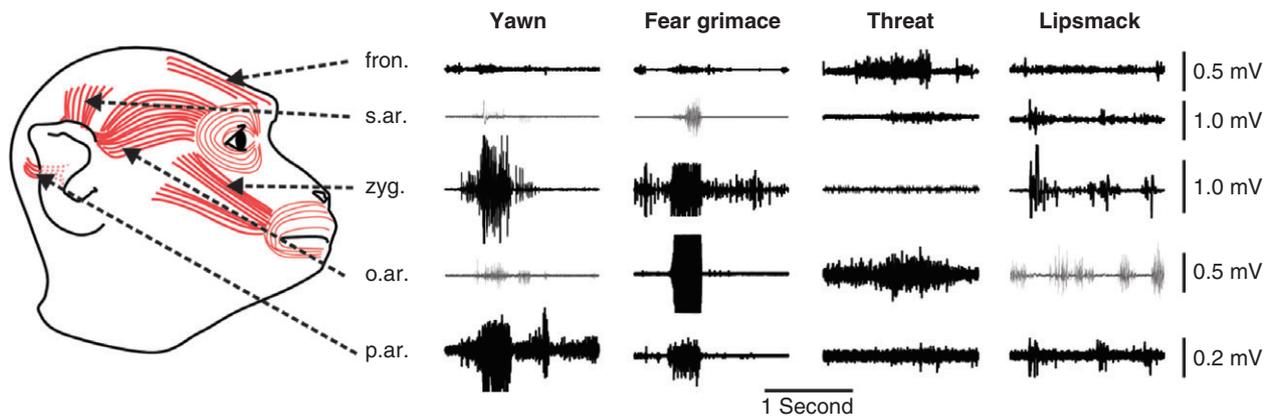
FIGURE 2 | Facial expressions provoked by viewing of videos of conspecifics elicit distinct patterns of EMG activity. Each row shows the raw EMG from five muscles: fron., frontalis; o.ar., orbito-auricularis; s.ar. and p.ar., superior and posterior auricularis, respectively, and zyg., zygomatic. Note the rhythmic and complementary bursting during lipsmacks. High amplitude electromyographic (EMG) signals of p.ar., zyg., and o.ar. are clipped in yawn and fear grimace.

videos blink.[48] The more the viewer monkey looked at the eyes of monkey in the videos, the stronger the observed eyeblink entrainment. Eyeblink entrainment in humans is considered a form of social coordination.[49–53] Preliminary results from our laboratory indicate that a small subset of neurons in the amygdala alter their firing during eyeblinks. The significance of these neural responses has yet to be determined.

Replacement of Static Images with Videos Led to the Discovery of Eye Cells

Even static images of faces are complex, multidimensional stimuli that contain information about identity, facial expression, gaze direction, familiarity, social status, and attractiveness.[54] It is likely, therefore, that more than one dimension contributes to the firing properties of face cells. Identity and facial expression have been the two most often studied dimensions. Consequently, it has been established that the majority of neurons in the monkey and human amygdala respond to face identity[24,25,55] and/or facial expression.[26,27,56]

When we replaced static images of faces with videos, we replicated the previously documented identity and expression-specific neural responses in the amygdala but also found that a fraction of neurons (~12% of the recorded neurons) were selectively activated by eye contact.[57] These cells were a subclass of a more broadly specialized class of cells that were active when the viewer looked at the eyes of the monkey in the video, regardless of its gaze direction.[57] The mere presence of eyes in the frame of video was not sufficient to activate the eye cells. They were activated at the expected latencies only after fixation onset on the eyes, and they ceased firing when the subject fixated on a different facial feature, even if that feature was only 2–3° of visual angle away from the eyes (Figure 3). This reinforces the previously mentioned link between attention and stimulus-selective activity in the amygdala. Based on their response properties, the eye contact cells were similar to canonical visually responsive neurons in the amygdala except that they increased their firing rate sixfold to sevenfold for eye contact compared to averted gaze. Eye cells did not appear localized to a particular nucleus or cluster of nuclei in the amygdala.

The observation that individual neurons in the temporal lobe can show great specificity for certain visual features, such as faces, hands, and more recently the eyes, is not new.[58–64] In fact, according to reductionist views, such highly specialized cells emerge as a result of convergent hierarchy in the visual system. It is unlikely, however, that the specificity of the eye cells in the amygdala is due to their role as 'gnostic units' as originally envisioned by Knorkski.[65] It is more likely that the eye cells attest to the social-emotional significance of the eyes because the amygdala is known to respond to the emotional significance rather than the sensory features of external stimuli.[66]

The presence of eye cells in the amygdala reinforces the idea that the amygdala processes some of the most arousing and emotionally meaningful stimuli in the environment and that it contains neural specializations for social behavior.

Social Behaviors in Response to Naturalistic Social Stimuli Led to the Discovery of Neurons in the Amygdala That Respond to the Production of Facial Expressions and to Touch

As previously shown by others and by our laboratory, monkeys respond to natural social stimuli with situation-appropriate facial expressions or other social behaviors.[35,36,38–45,57,67,68] When monkeys reciprocated the facial expressions of others, a subset of neurons in the amygdala increased their firing rate.[69,70] Neural activity aligned in time with the production of facial expressions raised the possibility that the amygdala plays a role in the production of facial expressions. A possible role for the amygdala
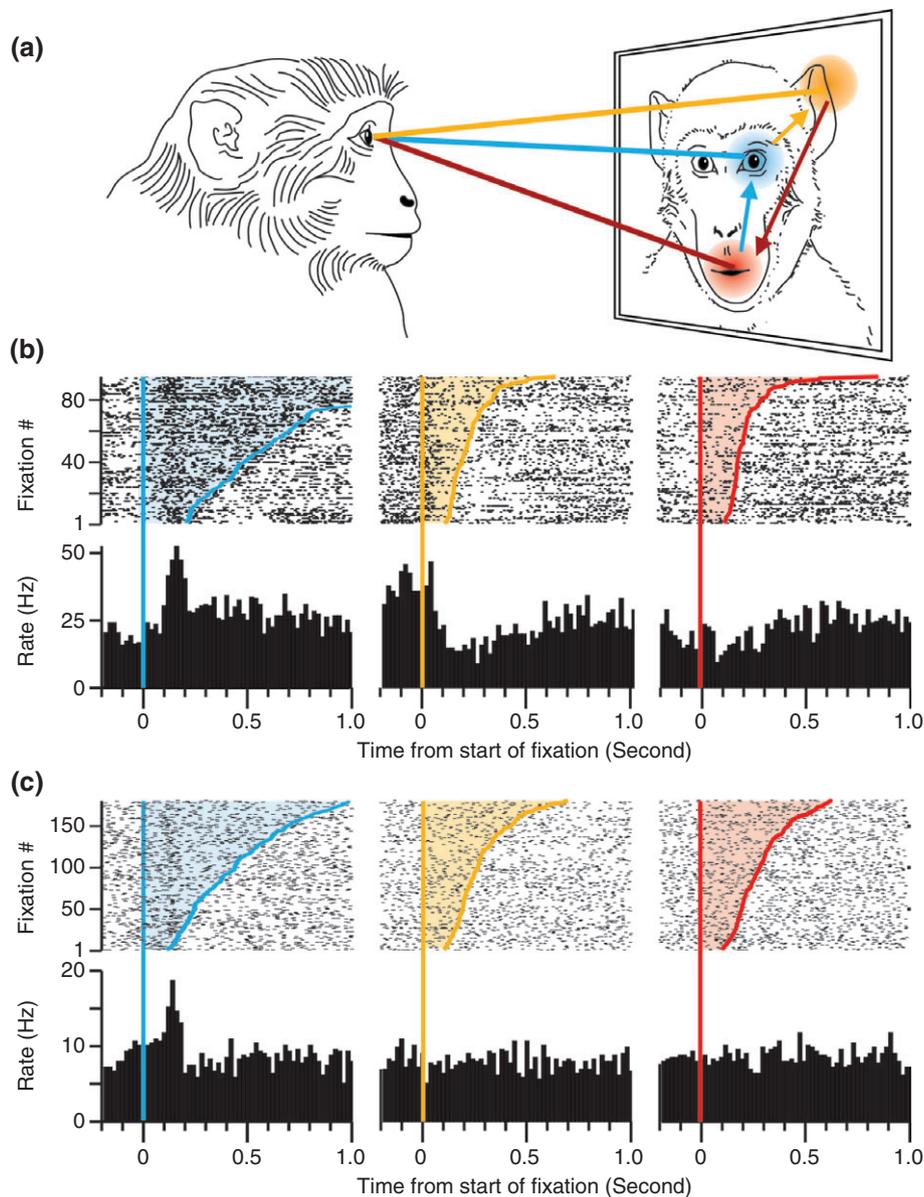
FIGURE 3 | Eye cells in the monkey amygdala. (a) Neural activity was analyzed during three types of fixations while viewing movies: fixations on the eyes that were preceded by fixations elsewhere (blue), fixations on another facial feature that were preceded by fixations on the eyes (yellow), and fixations on other features that were preceded by fixations on other areas (red). (b) Raster plots and peri-event time histograms illustrating the activity of two example neurons during the three fixation types listed above. Rasters are sorted by fixation duration. Fixations begin at 0 second and end at the curved line. This neuron showed increased firing rate (relative to the periods preceding this fixation) as long as the viewer monkey fixated eyes of the monkey in the video. Fixations on other facial features did not have the same effect. (c) This neuron showed a brief, phasic increase in firing rate during the first 200–300 milliseconds after the onset of each fixation on the eyes. (Reprinted with permission from Ref 57. Copyright 2014 Elsevier)

in the production of facial expressions is supported by the presence of direct projections from the amygdala to four of the five facial motor areas of the frontal lobe.[71]

We tested this hypothesis by implanting monkeys with intramuscular electromyographic (EMG) electrodes and monitoring simultaneously the facial musculature and neural activity in the amygdala.[69] These experiments rested on the premise that neural activity in a brain structure involved in the planning or execution of movements should precede EMG activity by ~20 milliseconds. The alignment of the onset of single-unit activity in the amygdala with the onset of EMG showed that a small number of neurons indeed changed their firing rate prior to the onset of EMG. Such activity patterns are consistent with a possible motor function of the amygdala. However, the majority of the neurons in the amygdala increased their firing *after* the onset of the EMG. This suggested that the observed neural activity was unlikely the signature of a motor command. It was more likely that this activity reflected proprioceptive feedback from the facial musculature and skin.[72] This interpretation required a more nuanced understanding of the motor and proprioceptive signaling in the amygdala.

The exquisite mobility of facial features and associated expressivity of the face are due to the direct insertion of muscles of facial expressions on the skin. These muscles contain few, if any, muscles spindles or Golgi tendon organss that send proprioceptive feedback signals to the brain.[73] Proprioceptive signals from the face arise instead from mechanoreceptors of the skin.[74] The implication of this innervation is that contraction of the facial musculature and *external mechanical stimulation* should activate more or less the same mechanoceptors of the face.[75] We, therefore, set out to test whether touching the face provoked neural activity in the amygdala. Blindfolded monkeys (blindfolding was necessary to eliminate confounds with visual responses to the humans sitting across from the monkey or from objects looming toward the face) quickly accepted touch by human hands, brushes, and blunt objects. We found that roughly 34% of neurons recorded in the monkey amygdala respond to cutaneous stimulation of the face[76] (Figure 4). The majority (98%) of the touch-sensitive neurons in the amygdala responded to multiple types of touch and had large, bilateral receptive fields covering a large portion of the face (e.g., both eyes and forehead). Ongoing experiments will determine whether these neurons discriminate between social

touch (delivered by a human) and touch via an inanimate object.

On occasion, the blindfold was removed and the monkeys were presented with stimuli that induced the production of facial expressions (Figure 4(b) and (d)). This activated the same neurons that responded to touch. Taken together these findings suggested that tactile neurons in the amygdala receive input from skin mechanoceptors that are activated both by touch and by compressions and stretches of the facial skin during the contraction of the underlying muscles.

Finding the tactile neurons in the amygdala was a direct consequence of exploring the neural basis of the natural behaviors originally elicited by videos with social content. Neural responses to tactile stimuli in the primate amygdala have not been previously reported and understanding their function will require further exploration. These neurons may serve as necessary sensory feedback during the production of facial expressions, as suggested by Livneh et al.[70]

It is also possible that the role of the tactile neurons is to evaluate the valence of touch stimuli. Whether pleasant or unpleasant, touch is an integral part of social communication among both human and nonhuman primates. Beyond reproductive behaviors and maternal care, affective touch in humans and grooming in monkeys plays an essential role in establishing and maintaining social bonds. It is not surprising, therefore, that the emerging literature on social touch elevated the skin to the role of a social organ.[77] In this framework, tactile neurons in the amygdala are equivalent to the visual or auditory neurons that process the emotional qualities of incoming social stimuli.

Neural Activity in the Amygdala during Dyadic Social Interactions Correspond to Decision and Action Both About the Self and the Social Partner

The neurophysiological studies that explored the role of the primate amygdala in social behavior have been focused primarily on social perception. With few exceptions, these studies involved passive viewing of visual stimuli with social content. Social perception in isolation can hardly stand as a proxy for real-life social behavior. Recent studies have gone beyond social perception and implemented dyadic interactions between monkeys to explore the neural basis of social decision-making. For example, Chang et al.[78] trained monkeys to play a modified version of the 'dictator' game and showed that neurons in the
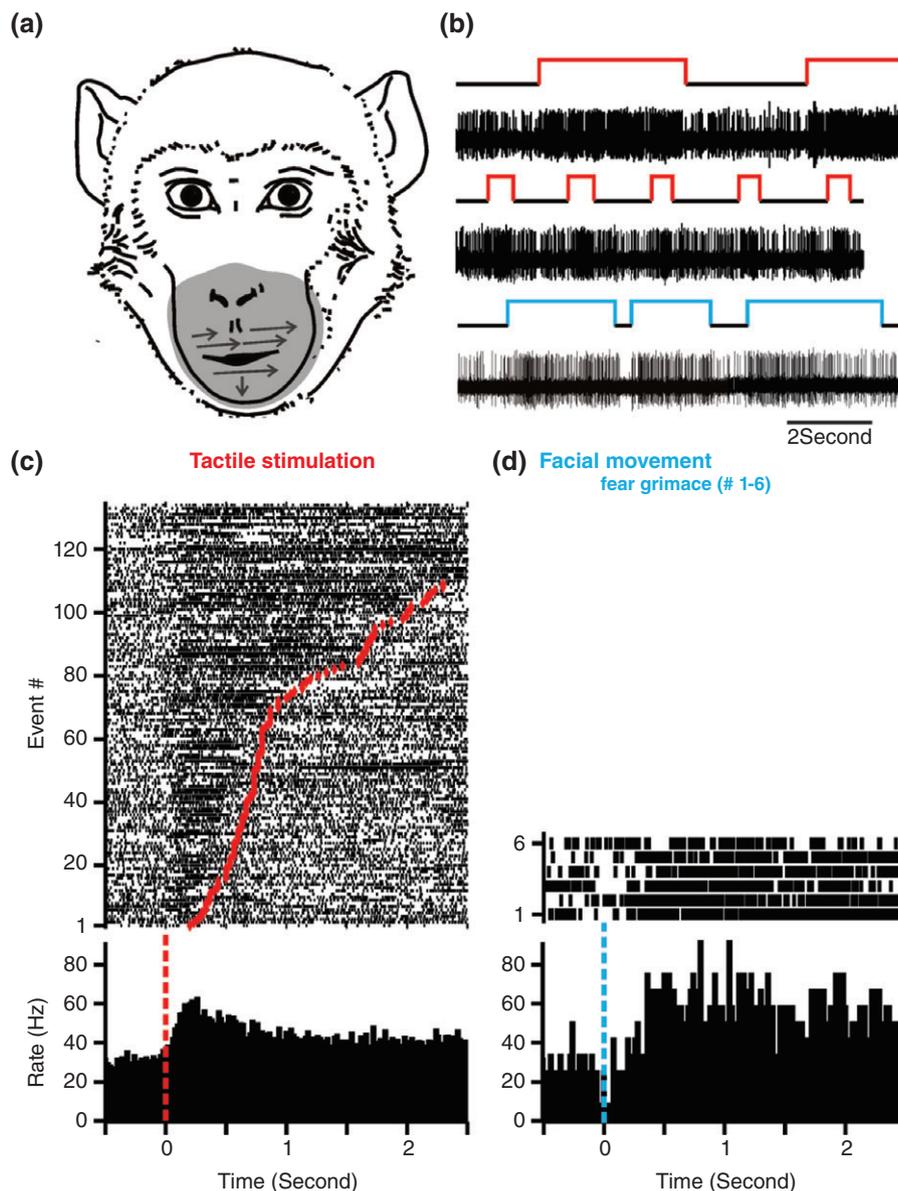
FIGURE 4 | Example tactile neuron from the monkey amygdala. (a) The area shaded in gray shows the receptive field of this neuron in the monkey face. The small arrows indicate the preferred direction of stimulation. (b) Raw traces of single-unit activity. The red lines above the raw traces indicate tactile stimulation of the face; the blue lines indicate the production of a facial expression (fear grimace). (c) Rasters and histograms aligned to the start of tactile stimulation (red dashed line) or the start of the facial expressions (blue dashed line). The rasters are sorted by the duration of stimulation; for each trial, the end of tactile stimulation is marked by a red dot. The neuron shown here responded to touch with a sustained increase in firing rate. (d) During bared-teeth displays (fear grimaces) produced by the monkey, this neuron showed patterns of activity that resembled the external stimulation of the muzzle. (Reprinted with permission from Ref 77. Copyright 2016 eNeuro)

amygdala encode similarly the value of rewards to self and rewards to others. When a computer delivered the same rewards, neurons in the amygdala failed to respond to the reward received by the social partner, suggesting that the action of delivering a reward is intrinsically linked to the representation of its value. Similar findings using dyadic interactions have been reported by Jazayeri et al.[79] indicating that

neurons in the primate amygdala encode both the value of the reward received and offered.

CONCLUSION

One paradox of animal studies in behavioral neurophysiology is that efforts to eliminate spurious factors have stripped the studied behaviors down to

their basic elements. These elements in isolation may not activate the entire brain circuit dedicated to support the full version of the behavior of interest. The unintended consequence of efforts to design 'clean' experiments involving multiple repeated trials is that the behavior becomes automatic and reward-motivated. Furthermore, it is possible that by the nth identical trial, this automatic, repetitive behavior activates only parts of the circuit of interest. Under these conditions, the observed neural activity may not be the entirely representative of the activity patterns required for the initial performance of the same behavior. This is of particular concern for social neuroscience. Animals rarely emit socially meaningful signals in the absence of a recipient, and rarely repeat these displays without reinforcement from a social partner. Moreover, a recent study shows that videos of interacting monkeys activate a network that is dedicated for processing social interactions.[80] This network includes the amygdala.

In the past 10 years, our laboratory explored the feasibility of recording neural activity from the amygdala under less restrictive experimental conditions. This has included the replacement of static images with videos and using different video stimuli for each trial. We also replaced single images with arrays of images containing multiple elements that competed for attention. In addition, we have physically interacted with monkeys when we applied tactile stimuli to the face. Furthermore, we have exploited the propensity of monkeys to 'interact' with the stimulus videos by engaging in eye contact and in the production of facial expressions. The outcome of these efforts was the discovery of new types of neural responses (eye contact cells, tactile-responsive cells) in the amygdala that point to functions that were previously not reported by studies designed based on reductionist principles. Indeed, the discovery of touch-responsive neurons has ushered in a welcome shift in focus from neural processes mediated by visual and auditory stimuli toward less well-explored sensory modalities. Most importantly, these results pave the way for future experiments that will replace videos with live interactions with conspecifics as already pioneered by a few laboratories.[70,78,81,82] The ideal development would be to implement in the laboratory closed-loop social interactions. The social brain evolved to process social signals and make social decisions in closed-loop interactions—and neural activity monitored under such conditions holds the promise of further exciting discoveries.

REFERENCES

1. Allman J, Miezin F, McGuinness E. Stimulus-specific responses from beyond the classical receptive field: neurophysiological mechanisms for local-global comparisons in visual neurons. *Annu Rev Neurosci* 1985, 8:407–430.

2. Gilbert CD, Wiesel TN. The influence of contextual stimuli on the orientation selectivity of cells in primary visual cortex of the cat. *Vision Res* 1990, 30:1689–1701.

3. Albright TD, Stoner GR. Contextual influences on visual processing. *Annu Rev Neurosci* 2002, 25:339–379.

4. Vinje WE, Gallant JL. Natural stimulation of the non-classical receptive field increases information transmission efficiency in V1. *J Neurosci* 2002, 22:2904–2915.

5. David SV, Gallant JL. Predicting neuronal responses during natural vision. *Network: Comput Neural Syst* 2005, 16:239–260.

6. Gallant JL, Connor CE, Van Essen DC. Neural activity in areas V1, V2 and V4 during free viewing of natural scenes compared to controlled viewing. *Neuroreport* 1998, 9:2153–2158.

7. Pinto N, Cox DD, DiCarlo JJ. Why is real-world visual object recognition hard? *PLoS Comput Biol* 2008, 4:e27.

8. Krakauer JW, Ghazanfar AA, Gomez-Marin A, MacIver MA, Poeppel D. Neuroscience needs behavior: correcting a reductionist bias. *Neuron* 2017, 93:480–490.

9. Gross CG, Rocha-Miranda CED, Bender DB. Visual properties of neurons in inferotemporal cortex of the Macaque. *J Neurophysiol* 1972, 35:96–111.

10. Bruce C, Desimone R, Gross CG. Visual properties of neurons in a polysensory area in superior temporal

sulcus of the Macaque. *J Neurophysiol* 1981, 46:369–384.

11. Perrett DI, Rolls ET, Caan W. Visual neurons responsive to faces in the monkey temporal cortex. *Exp Brain Res* 1982, 47:329–342.

12. Desimone R. Face-selective cells in the temporal cortex of monkeys. *J Cogn Neurosci* 1991, 3:1–8.

13. Rolls ET, Baylis GC, Hasselmo ME. The responses of neurons in the cortex in the superior temporal sulcus of the monkey to band-pass spatial frequency filtered faces. *Vision Res* 1987, 27:311–326.

14. Hasselmo ME, Rolls ET, Baylis GC. The role of expression and identity in the face-selective responses of neurons in the temporal visual cortex of the monkey. *Behav Brain Res* 1989, 32:203–218.

15. Young MP, Yamane S. Sparse population coding of faces in the inferotemporal cortex. *Science* 1992, 256:1327–1331.

16. Perrett DI, Oram MW, Harries MH, Bevan R, Hietanen JK, Benson PJ, Thomas S. Viewer-centred and object-centred coding of heads in the Macaque temporal cortex. *Exp Brain Res* 1991, 86:159–173.

17. Wallis G, Rolls ET. Invariant face and object recognition in the visual system. *Prog Neurobiol* 1997, 51:167–194.

18. Leopold DA, Rhodes G, Müller KM, Jeffery L. The dynamics of visual adaptation to faces. *Proc Biol Sci* 2005, 272:897–904.

19. Tsao DY, Freiwald WA, Tootell RB, Livingstone MS. A cortical region consisting entirely of face-selective cells. *Science* 2006, 311:670–674.

20. Freiwald WA, Tsao DY. Functional compartmentalization and viewpoint generalization within the macaque face-processing system. *Science* 2010, 330:845–851.

21. McMahon DB, Jones AP, Bondar IV, Leopold DA. Face-selective neurons maintain consistent visual responses across months. *Proc Natl Acad Sci* 2014, 111:8251–8256.

22. Sanghera MK, Rolls ET, Roper-Hall A. Visual responses of neurons in the dorsolateral amygdala of the alert monkey. *Exp Neurol* 1979, 63:610–626.

23. Leonard CM, Rolls ET, Wilson FAW, Baylis GC. Neurons in the amygdala of the monkey with responses selective for faces. *Behav Brain Res* 1985, 15:159–176.

24. Nakamura K, Mikami A, Kubota K. Activity of single neurons in the monkey amygdala during performance of a visual discrimination task. *J Neurophysiol* 1992, 67:1447–1463.

25. Fried I, MacDonald KA, Wilson CL. Single neuron activity in human hippocampus and amygdala during recognition of faces and objects. *Neuron* 1997, 18:753–765.

26. Kuraoka K, Nakamura K. Responses of single neurons in monkey amygdala to facial and vocal emotions. *J Neurophysiol* 2007, 97:1379–1387.

27. Gothard KM, Battaglia FP, Erickson CA, Spitler KM, Amaral DG. Neural responses to facial expression and face identity in the monkey amygdala. *J Neurophysiol* 2007, 97:1671–1683.

28. Rutishauser U, Tudusciuc O, Wang S, Mamelak AN, Ross IB, Adolphs R. Single-neuron correlates of atypical face processing in autism. *Neuron* 2013, 80:887–899.

29. Minxha J, Mosher C, Morrow JK, Mamelak AN, Adolphs R, Gothard KM, Rutishauser U. Fixations gate species-specific responses to free viewing of faces in the human and Macaque amygdala. *Cell Rep* 2017, 18:878–891.

30. Sheinberg DL, Logothetis NK. Noticing familiar objects in real world scenes: the role of temporal cortical neurons in natural vision. *J Neurosci* 2001, 21:1340–1350.

31. Adolphs R, Gosselin F, Buchanan TW, Tranel D, Schyns P, Damasio AR. A mechanism for impaired fear recognition after amygdala damage. *Nature* 2005, 433:68–72.

32. Spezio ML, Huang PYS, Castelli F, Adolphs R. Amygdala damage impairs eye contact during conversations with real people. *J Neurosci* 2007, 27:3994–3997.

33. Dal Monte O, Costa VD, Noble PL, Murray EA, Averbeck BB. Amygdala lesions in *Rhesus macaques* decrease attention to threat. *Nat Commun* 2014, 6:10161.

34. Davis M, Whalen PJ. The amygdala: vigilance and emotion. *Mol Psychiatry* 2001, 6:13.

35. O'Toole AJ, Roark DA, Abdi H. Recognizing moving faces: a psychological and neural synthesis. *Trends Cogn Sci* 2002, 6:261–266.

36. Ghazanfar AA, Maier JX, Hoffman KL, Logothetis NK. Multisensory integration of dynamic faces and voices in Rhesus monkey auditory cortex. *J Neurosci* 2005, 25:5004–5012.

37. Matsumoto N, Okada M, Sugase-Miyamoto Y, Yamane S, Kawano K. Population dynamics of face-responsive neurons in the inferior temporal cortex. *Cereb Cortex* 2005, 15:1103–1112.

38. Machado CJ, Bliss-Moreau E, Platt ML, Amaral DG. Social and nonsocial content differentially modulates visual attention and autonomic arousal in *Rhesus macaques*. *PLoS One* 2011, 6:e26598.

39. Furl N, Hadj-Bouziane F, Liu N, Averbeck BB, Ungerleider LG. Dynamic and static facial expressions decoded from motion-sensitive areas in the macaque monkey. *J Neurosci* 2012, 32:15952–15962.

40. Ghazanfar AA. Multisensory vocal communication in primates and the evolution of rhythmic speech. *Behav Ecol Sociobiol* 2013, 67:1441–1448.

41. Polosecki P, Moeller S, Schweers N, Romanski LM, Tsao DY, Freiwald WA. Faces in motion: selectivity of

Macaque and human face processing areas for dynamic stimuli. *J Neurosci* 2013, 33:11768–11773.

42. Diehl MM, Romanski LM. Responses of prefrontal multisensory neurons to mismatching faces and vocalizations. *J Neurosci* 2014, 34:11233–11243.

43. Russ BE, Leopold DA. Functional MRI mapping of dynamic visual features during natural viewing in the *Macaque*. *Neuroimage* 2015, 109:84–94.

44. McMahon DB, Russ BE, Elnaiem HD, Kurnikova AI, Leopold DA. Single-unit activity during natural vision: diversity, consistency, and spatial sensitivity among AF face patch neurons. *J Neurosci* 2015, 35:5537–5548.

45. Mosher CP, Zimmerman PE, Gothard KM. Videos of conspecifics elicit interactive looking patterns and facial expressions in monkeys. *Behav Neurosci* 2011, 125:639.

46. Putnam PT, Roman JM, Zimmerman PE, Gothard KM. Oxytocin enhances gaze-following responses to videos of natural social behavior in adult male Rhesus monkeys. *Psychoneuroendocrinology* 2016, 72:47–53.

47. Chevalier-Skolnikoff S. Facial expression of emotion in nonhuman primates. In: Ekman P, ed. *Darwin and Facial Expression: A Century of Research in Review*. New York: Academic Press; 1973, 11–90.

48. Ballesta S, Mosher CP, Szep J, Fischl KD, Gothard KM. Social determinants of eyeblinks in adult male *Macaques*. *Sci Rep* 2016, 6.

49. Nakano T, Yamamoto Y, Kitajo K, Takahashi T, Kitazawa S. Synchronization of spontaneous eyeblinks while viewing video stories. *Proc Biol Sci* 2009, 276:3635–3644.

50. Nakano T, Kato N, Kitazawa S. Lack of eyeblink entrainments in autism spectrum disorders. *Neuropsychologia* 2011, 49:2784–2790.

51. Cummins F. Gaze and blinking in dyadic conversation: a study in coordinated behaviour among individuals. *Lang Cogn Process* 2012, 27:1525–1549.

52. Trutoiu, LC, Hodgins, JK, Cohn, JF The temporal connection between smiles and blinks. In: *Proceedings of the 10th IEEE International Conference and Workshops on Automatic Face and Gesture Recognition (FG)*, Washington, DC, May 30–June 3, 2017. IEEE, 2013, 1–6.

53. Hömke P, Holler J, Levinson SC. Eye blinking as addressee feedback in face-to-face conversation. *Res Lang Soc Interact* 2017, 50:1–17.

54. Leopold DA, Rhodes G. A comparative view of face perception. *J Comp Psychol* 2010, 124:233.

55. Mormann F, Niediek J, Tudusciuc O, Quesada CM, Coenen VA, Elger CE, Adolphs R. Neurons in the human amygdala encode face identity, but not gaze direction. *Nat Neurosci* 2015, 18:1568–1570.

56. Wang S, Tudusciuc O, Mamelak AN, Ross IB, Adolphs R, Rutishauser U. Neurons in the human amygdala selective for perceived emotion. *Proc Natl Acad Sci* 2014, 111:E3110–E3119.

57. Mosher CP, Zimmerman PE, Gothard KM. Neurons in the monkey amygdala detect eye contact during naturalistic social interactions. *Curr Biol* 2014, 24:2459–2464.

58. Barlow HB. Single units and sensation: a neuron doctrine for perceptual psychology? *Perception* 1972, 1:371–394.

59. Blakemore C, Muncey JP, Ridley RM. Stimulus specificity in the human visual system. *Vision Res* 1973, 13:1915–1931.

60. Marr D. *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information*, vol. 2. New York, NY: Henry Holt and Co. Inc; 1982, 2–4.

61. Churchland PM. *Scientific Realism and the Plasticity of Mind*. Cambridge: Cambridge University Press; 1986.

62. Logothetis NK, Sheinberg DL. Visual object recognition. *Annu Rev Neurosci* 1996, 19:577–621.

63. Tanaka K. Inferotemporal cortex and object vision. *Annu Rev Neurosci* 1996, 19:109–139.

64. Gross CG. *Brain, Vision, Memory: Tales in the History of Neuroscience*. Cambridge, MA: MIT Press; 1999.

65. Knorkski J. *Integrative Activity of the Brain: An Inter-Disciplinary Approach*. Chicago, IL: University of Chicago Press; 1967.

66. Paton JJ, Belova MA, Morrison SE, Salzman CD. The primate amygdala represents the positive and negative value of visual stimuli during learning. *Nature* 2006, 439:865–870.

67. Paukner A, Anderson JR. Video-induced yawning in stumptail *Macaques* (*Macaca arctoides*). *Biol Lett* 2006, 2:36–38.

68. Anderson JR, Kuroshima H, Paukner A, Fujita K. Capuchin monkeys (*Cebus apella*) respond to video images of themselves. *Anim Cogn* 2009, 12:55–62.

69. Fuglevand, AJ, Zimmerman, PE, Mosher, CP, & Gothard, KM Single unit activity in the primate amygdala during the production of facial expressions. Program No. 402.05. 2012 Neuroscience Meeting Planner, New Orleans, LA: Society for Neuroscience, 2012

70. Livneh U, Resnik J, Shohat Y, Paz R. Self-monitoring of social facial expressions in the primate amygdala and cingulate cortex. *Proc Natl Acad Sci* 2012, 109:18956–18961.

71. Morecraft RJ, McNeal DW, Stilwell Morecraft KS, Gedney M, Ge J, Schroeder CM, Van Hoesen GW. Amygdala interconnections with the cingulate motor cortex in the Rhesus monkey. *J Comp Neurol* 2007, 500:134–165.

72. Mosher, CP, Zimmerman, PE, & Gothard, KM Tactile stimulation of the face activates single units in the monkey amygdala. Program No. 402.01. 2012 Neuroscience Meeting Planner. New Orleans, LA: Society for Neuroscience, 2012.

73. Stål P, Eriksson PO, Eriksson A, Thornell LE. Enzyme-histochemical differences in fibre-type between the human major and minor zygomatic and the first dorsal interosseus muscles. *Arch Oral Biol* 1987, 32:833–841.

74. Ito T, Ostry DJ. Somatosensory contribution to motor learning due to facial skin deformation. *J Neurophysiol* 2010, 104:1230–1238.

75. Trulsson M, Johansson RS. Orofacial mechanoreceptors in humans: encoding characteristics and responses during natural orofacial behaviors. *Behav Brain Res* 2002, 135:27–33.

76. Mosher CP, Zimmerman PE, Fuglevand AJ, Gothard KM. Tactile stimulation of the face and the production of facial expressions activate neurons in the primate amygdala. *eNeuro* 2016, 3: ENEURO-0182.

77. Löken LS, Olausson H. The skin as a social organ. *Exp Brain Res* 2010, 204:305–314.

78. Chang SW, Gariépy JF, Platt ML. Neuronal reference frames for social decisions in primate frontal cortex. *Nat Neurosci* 2013, 16:243–250.

79. Jazayeri M, Ballesta S, Duhamel J-R. Social decision-making in non-human primates. In: Dreher J-C, Tremblay L, eds. *Decision Neuroscience*. London, UK: Academic Press; 2016, 179–185.

80. Sliwa J, Freiwald WA. A dedicated network for social interaction processing in the primate brain. *Science* 2017, 356:745–749.

81. Ballesta S, Duhamel JR. Rudimentary empathy in Macaques' social decision-making. *Proc Natl Acad Sci* 2015, 112:15516–15521.

82. Dal Monte O, Piva M, Morris JA, Chang SW. Live interaction distinctively shapes social gaze dynamics in *Rhesus macaques*. *J Neurophysiol* 2016, 116:1626–1643.