

MORAN CERF, ERIC GREENLEAF, TOM MEYVIS, and VICKI G. MORWITZ*

This article introduces the method of single-neuron recording in humans to marketing and consumer researchers. First, the authors provide a general description of this methodology, discuss its advantages and disadvantages, and describe findings from previous single-neuron human research. Second, they discuss the relevance of this method for marketing and consumer behavior and, more specifically, how it can be used to gain insights into the areas of categorization, sensory discrimination, reactions to novel versus familiar stimuli, and recall of experiences. Third, they present a study designed to illustrate how single-neuron studies are conducted and how data from them are processed and analyzed. This study examines people's ability to up-regulate (i.e., enhance) the emotion of fear, which has implications for designing effective fear appeals. The study shows that the firing rates of neurons previously shown to respond selectively to fearful content increased with emotion enhancement instructions, but only for a video that did not automatically evoke substantial fear. The authors discuss how the findings help illustrate which conclusions can and cannot be drawn from single-neuron research.

Keywords: neuroscience, emotions, consumer communication, fear appeals, climate change

Online Supplement: <http://dx.doi.org/10.1509/jmr.13.0606>

Using Single-Neuron Recording in Marketing: Opportunities, Challenges, and an Application to Fear Enhancement in Communications

Neuroscience has become an increasingly popular method for studying questions of interest to marketers and

*Moran Cerf is Donald P. Jacobs Professor of Business and Neuroscience, Kellogg School of Management, Northwestern University (e-mail: m-cerf@kellogg.northwestern.edu). Eric Greenleaf is Professor of Marketing (e-mail: egreenle@stern.nyu.edu), Tom Meyvis is Professor of Marketing and Peter Drucker Faculty Fellow (e-mail: tmeyvis@stern.nyu.edu), and Vicki G. Morwitz is Harvey Golub Professor of Business Leadership and Professor of Marketing (e-mail: vmorwitz@stern.nyu.edu), Stern School of Business, New York University. The article benefited from discussions with the participants at various academic conferences, including the 2012 Society for Consumer Psychology Conference in Florence, the 2012 Association for Consumer Research in Vancouver, the 2012 Marketing Science Conference in Boston, and the 2013 Consumer Neuroscience Satellite Symposium in Lausanne, Switzerland. The support of grant 5R21DA24423-2 from the National Institutes of Health and National Institute on Drug Abuse is gratefully acknowledged.

consumer researchers. Examining people's brain activity while they perform consumer behavior tasks has deepened understanding of how people perceive and process information, experience emotions, and make decisions. Techniques such as functional magnetic resonance imaging (fMRI) and electroencephalogram (EEG), originally developed for medical diagnostic purposes, have created insights that cannot be obtained through other consumer research methods. However, by their very nature, these techniques test a fairly large part of the brain at any one time. Such aggregation is not a problem insofar as different neural regions play specialized parts in human thought and perception. For example, studies using these methods have identified the specialized functions of different neural regions for each of the five senses, as well as for integrating information, making decisions, and experiencing emotions (see, e.g., Driver and

Noesselt 2008; Kassam et al. 2013; Phan et al. 2002; Prabhakaran et al. 2000; Sanfey et al. 2003).

However, the basic building blocks of the brain are neurons. Neurons in the same part of the brain and even adjacent to each other can have very different functions and respond to different stimuli (Cerf and MacKay 2011). Thus, much can be learned, in terms of how the human brain functions, by studying the activity of individual neurons. Yet even a single voxel in an fMRI study typically contains several thousand neurons (Grill-Spector and Malach 2001), and the differences in brain activation observable using fMRI or EEG are due to the collective activity of many thousands or even millions of neurons.

While considerable research has examined the activity of individual neurons, most of this work has studied nonhuman animals, such as rats or monkeys (Shadlen and Kiani 2013), though this research has provided many insights applicable to human behavior and economic decision making (Glimcher and Fehr 2014; Levy and Glimcher 2012). More recently, researchers have begun studying the activities of single neurons in humans. Certain surgical treatments for patients with epilepsy require placing electrodes, either as probes fairly deep in the brain or as a grid on the surface of the cortex (Fried et al. 2014). Thin microwires, placed in the hollow center of these probes, often contact neurons and give reliable readings of individual neurons for a relatively extended period. Though understandably absent in the marketing literature, single-neuron research in humans has provided insights of interest to marketers and consumer researchers.

The purposes of this article are to introduce to the marketing audience single-neuron research in humans and the potential applications of that research to issues in marketing and consumer behavior and to provide instructive examples of how single-neuron research is carried out and how data from individual neurons are analyzed and conclusions reached. We first review some prior findings from single-neuron research in humans and briefly describe the single-neuron methodology in humans. Then, we discuss how this method can be used to examine several relevant questions in marketing and consumer research. Next, we present a single-neuron study to illustrate the procedure of single-neuron research, as well as its promise and challenges. This study examines people's ability to enhance feelings of fear when watching videos, a communication medium often used for fear appeals. We find that though people do have this ability, in the study they could do so only when watching a video that did not automatically evoke a substantial level of fear. We discuss the advantages and limitations of our study to illustrate the advantages and limitations of single-neuron research compared with other observational methods in neuroscience.

SINGLE-NEURON RESEARCH IN HUMANS: METHODOLOGY AND MOTIVATION

Brain Activity at the Single-Neuron Level

Firing neurons create tiny electrical impulses, which they communicate to other neurons using connections called "synapses." This network is considered the building block of all neural activity and thought. Neural firings take place quite rapidly—a single firing sequence, which creates a

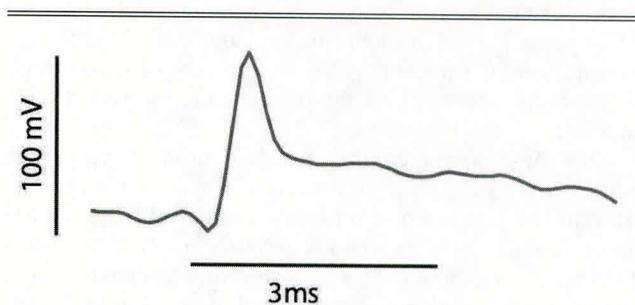
spike in the neuron's voltage, typically takes only a couple of milliseconds. Most neurons have a distinctive firing signature, shown in Figure 1, starting with a rest voltage that quickly increases to a peak and then decreases, creating a firing spike. Changes in a neuron's activity are usually reflected by a significant increase or decrease in the frequency of firing spikes, with different neurons becoming more or less active in response to certain types of stimuli or cognitive activity. Examples include neurons that increase their firing frequency in response to stimuli related to a specific person (Cerf et al. 2010), to familiar versus novel stimuli (Rutishauser, Mamelak, and Schuman 2006), or to objects (Fried et al. 2002).

The Single-Neuron Methodology in Humans

Initially, single-neuron work was done exclusively with nonhuman animals. However, advances in surgical treatments for epilepsy patients whose seizures could not be managed by pharmacological means created an opportunity to observe single-neuron activity in humans. Epileptic seizures, which are massive and uncontrollable firings of neurons, usually originate in a particular region of the brain for a given patient. Physicians found that surgically removing the area of origin could stop many patients' seizures, permanently curing them of epilepsy.

To identify the exact neural region where seizures originate, neurosurgeons implant thin, hollow electrodes or probes (typically 1 to 12), about a millimeter in diameter and up to several inches long, into several areas surrounding the suspected site of seizure origin. The implant sites are determined only by clinical criteria. Probes are often implanted in the medial-temporal lobe, frontal areas, or motor cortices and less often, or not at all, implanted in other areas. In general, the implant sites are associated with neural functions such as memory consolidation or retrieval (hippocampus, entorhinal cortex), fear and social behavior encoding (amygdala), high-level perception (all), navigation (parahippocampal cortex), analysis and perception of specific concepts (right amygdala and parahippocampal cortex), high-level cognitive control and regulation (orbitofrontal cortex), motor planning (supplementary motor area), and general planning and volition as well as error correction

Figure 1
ILLUSTRATIVE FIRING SPIKE FOR A HUMAN NEURON TAKEN
FROM OUR DATA



Notes: Typical firing spike: A trace of a single spike from a neuron in the right amygdala of patient 1.

(cingulate). Many studies have suggested that various other functions are identified in these areas (Jenison et al. 2011; Plassmann, Ramsøy, and Milosavljevic 2012; for a review on human electrophysiology, see Mukamel and Fried 2012).

The probes can also be used to detect impulses from individual neurons. During probe implantation, microelectrodes, which are very thin wires, can be inserted through the probes and allowed to slightly branch out into the brain at the probes' ends. The impedance of the wire makes it ideal for recording immediately adjacent neurons, while avoiding picking up noise from neurons outside the immediate area, due to large signal decay with distance. Several microwires are usually inserted into each probe; for example, we used eight microwires per probe, creating eight recording channels. The signals detected from neurons vary across microwires, and they include detecting a signal from a single neuron, detecting signals from several neurons, and not detecting any individual neuron activity (for a discussion, see Fried et al. 2014). The proportion of microwires that detect neurons varies but tends to average around 10% to 20% (Waydo et al. 2006). When a microwire detects signals from more than one neuron, researchers can use a technique called "spike sorting" (discussed subsequently) to separate signals from the individual neurons.

After the electrodes are implanted, patients remain in the hospital for one to three weeks while neurosurgeons wait for them to have seizures. During this time, doctors monitor the impulses from the probes, and the patients are recorded on video. The electrodes are connected to a computer that collects the data from the electrodes at a high sampling rate (typically 28–30 KHz), which is fast enough to accurately capture and characterize the spiking activity of neurons. Additional metrics are also recorded, such as heart activity, respiration, and skeletal muscle activity, and sometimes other measures, such as microdialysis, are used.

The patients are connected to the recording equipment, and though they must stay in the hospital room, they have some mobility and can often sit at a desk in front of a laptop. During their stay, patients are offered the opportunity to participate in research studies. The topics that can be studied depend on where in the brain the electrodes are implanted and from which brain regions neurons are measured. Given the brain regions where electrodes are usually implanted, these studies often focus on cognitive functions such as memory and perception, navigation in virtual space, issues related to motor planning, control or mirroring activities, and issues related to emotions and control. The study we describe herein falls in the last category. Patients typically participate in multiple studies, conducted by different researchers, in a single day. These studies tend to be spaced a few hours apart to give the patient time to rest between studies.

Surgeons cannot control which neurons a particular microwire will contact or, indeed, if it will contact any at all. Thus, while neurons in particular areas of the brain are more likely to be activated for certain cognitive functions than for others, there is no way to ensure that signals from a neuron with a particular function will be measured. Fortunately, there is substantial redundancy in neural functioning, which increases the odds of identifying responsive neurons

even using a limited set of stimuli. Research has estimated that between one million and five million neurons respond to even fairly specific stimuli, concepts, or cognitive tasks (Waydo et al. 2006). Given the uncertainty about which neurons will be monitored in any given study, researchers must design their studies on location, working with each participant, using a sequential method. In a first phase, participants are exposed to multiple stimuli or asked to perform a series of tasks. Researchers must then determine which stimuli or tasks the neurons being monitored have responded to and then, in a second phase, focus on these particular stimuli and tasks with that participant. For example, marketing researchers could present a large set of brands to participants, after which they could conduct a study with the particular brands to which some of the neurons responded.

Note that though we focus on the method involving microwires, alternative methods, such as electrocorticography and intracranial EEG, use electrodes placed on the surface of an exposed brain to record activity from the cortex alone. The recorded activity is typically field voltage rather than the activity of individual neurons, but it still benefits from direct access to the brain of a human subject.

Comparison of the Single-Neuron Approach with Other Methods

One purpose of this article is to help researchers identify questions that single-neuron analysis is well suited to address, either by itself or in combination with other methods, on the basis of its advantages and disadvantages compared with other research methods. Along with other neuroscience methods, such as fMRI and EEG, single-neuron research has some potential advantages over more conventional market research methods. For example, unlike self-reports and surveys, neuroscience methods can record activities that participants may not be aware of, may not be able to report accurately, or might distort with possible demand effects, social desirability biases, or response styles. Neuroscience methods can also measure the activation of concepts *during* a task rather than by queries *after* a task, and they can often do so at a more fine-grained level (i.e., detecting differences between related concepts in both activation strength and onset). Moreover, unlike other psychophysical measures (e.g., facial expressions, blood pressure, skin conductance), neuroscience methods can detect subtle emotional responses (that may not result in observable changes in facial expressions or blood pressure) as well as cognitive processes that do not have a strong emotional or motivational component.

Single-neuron analysis also has some advantages over other neuroscience methods. It has a finer spatial resolution, at the level of a single neuron. In comparison, fMRI's resolution is a voxel containing anywhere from approximately 600,000 to 16 million neurons, while EEG typically has a much coarser spatial resolution of hundreds of millions of neurons. This higher spatial resolution enables researchers to measure the activation of highly specific categories, concepts, and emotions that may not be separable with these other neuroscience methods. This ability is particularly important because adjacent neurons often handle different tasks (Cerf et al. 2010). Single-neuron analysis also has a

finer temporal resolution (as fast as 20 microseconds in current acquisition systems) than fMRI scans (currently in the range of 1.5–3 seconds). An important implication of this high temporal resolution is that psychological mechanisms, some of which occur in a matter of milliseconds, can be observed in real time, allowing researchers to observe their temporal order. That is, single-neuron analysis can measure not only the neural *consequences* of cognitive processes but also the cognitive processes themselves, such as the reconstruction of past experiences, the formation of associations, and the learning of relationships.

However, the single-neuron method requires substantially more financial and human resources than other methods, including EEG and fMRI. Moreover, while EEG and fMRI enable researchers to monitor activity in the entire brain, the single-neuron method is limited to only a small set of neurons, and the areas implanted are limited and determined by clinical criteria for epilepsy neurosurgery. The population of participants is currently restricted to epilepsy patients, and the success of an individual study is highly dependent on exogenously determined or random factors, such as the location of the probes in the brain, whether any individual neurons are contacted, and whether these neurons are selectively activated by any of the stimuli of interest. Thus, single-neuron analysis makes best use of its advantages in market research when researchers want to examine neural functioning, through firing rates, for fairly specific psychological and behavioral constructs and have research questions that require high temporal and/or spatial resolution.

EXISTING SINGLE-NEURON RESEARCH IN HUMANS WITH IMPLICATIONS FOR MARKETING RESEARCH

Much of the single-neuron research in humans has focused on basic neural processes of interest to the greater neuroscience community, such as memory, perception, navigation, or neural coding. Understandably, this research has not focused on the usefulness of these findings to applied fields such as marketing. However, some of the findings do have relevance for marketing and consumer behavior. We next describe a selection of these findings, summarized in Table 1, to illustrate the potential of single-neuron research in humans for marketing research.

Categorization

Consumers' perceptions and decisions often depend on how they categorize products, brands, and people (Loken 2006). Categorization processes influence whether a product is regarded as addressing a need, whether a brand is included in the consideration set, and whether an employee is perceived as a serviceperson or a salesperson. Moreover, brands themselves can serve as categories, with brand attitudes transferring to brand extensions depending on whether these extensions are categorized as part of the brand (Boush and Loken 1991). Although consumers can often verbalize well-established category associations, these associations are more challenging to measure when they are unconscious, spontaneous, or fleeting. In these circumstances, single-neuron research could be informative given that single neurons react to activation of specific categories. For example, neurons in the hippocampus, entorhinal cor-

Table 1
POTENTIAL APPLICATIONS OF SINGLE-NEURON RESEARCH TO MARKETING

Topic	Examples of Single-Neuron Research Studying This Topic	Potential Applications to Marketing
Categorization	<ul style="list-style-type: none"> •Neurons responding to specific categories (Kreiman, Koch, and Fried 2000) •Neurons responding to specific instances of a category (Quian Quiroga et al. 2005) 	<ul style="list-style-type: none"> •Product categorization •Consideration set formation •Brand confusion •Brand associations •Brand extensions
Sensory discrimination	<ul style="list-style-type: none"> •Subconscious neural discrimination between tones and between natural versus artificial sounds (Bitterman et al. 2008) 	<ul style="list-style-type: none"> •Product changes •Conscious versus unconscious awareness of product differences (consumer segmentation)
Reactions to novel versus familiar stimuli	<ul style="list-style-type: none"> •Novelty and familiarity neurons, predicting stimuli as novel versus familiar (Rutishauser, Mamelak, and Schuman 2006) 	<ul style="list-style-type: none"> •Novelty versus familiarity effects on fluency and preference •Measuring fluency effects of repeated exposure •Understanding the different ways of creating fluency •Remembering versus knowing (feeling familiar with) a consumer event
Recalling experiences	<ul style="list-style-type: none"> •Neurons responding to both encoding and recall of film clips (Gelbard-Sagiv et al. 2008) 	<ul style="list-style-type: none"> •Customer satisfaction •Recall of message content •Reconstruction of consumption experiences (e.g., peak–end effects) •Construction of preferences
Regulation of thoughts	<ul style="list-style-type: none"> •Neural reactions to the enhancement and suppression of thoughts regarding objects and to the delivery of feedback (Cerf et al. 2010) 	<ul style="list-style-type: none"> •Emotion enhancement, such as fear appeals (example study in this article) •Emotion suppression •Self-control •Consumer goal pursuit

tex, and amygdala changed their firing rate when research participants viewed photos of objects in particular categories, such as food items, famous people, and animals (Kreiman, Koch, and Fried 2000). Kreiman, Koch, and Fried (2000) found neurons that fired for more than one category, neurons that showed *reduced* firing rates when stimuli in a category were presented, and neurons that increased firing rates when these stimuli were removed from sight.

Later work has identified neurons with even more selective categorization (Quiñones Quiroga et al. 2005). These neurons increased their activity in response to particular instances of a category, such as specific people, landmark buildings, or animals. Moreover, they responded across different representation modes of the same concept, such as a photo of the actress Halle Berry, a photo of her playing a role in the movie *Catwoman*, and her spelled name. These responses also could identify when a participant confused different, but similar, stimuli as being the same, such as the Sydney Opera House and the Bahá'í Temple in New Delhi. In a branding context, this implies that single-neuron studies have the potential to detect brand confusion as well as the extent to which different brand representations (e.g., logos), brand associations (e.g., celebrity endorsers), and brand extensions activate the core brand concept.

Subsequent research has also found hierarchical ordering in the processing of information, by measuring the response latencies of neurons from various sites in the brain (Mormann et al. 2008). These latencies could convey valuable information insofar as they are indicators of additional processing. For example, slower activation of a neuron that responds to a specific brand could be a measure of the personal importance of that brand (e.g., its relationship to the self). Note that this is quite different from the meaning of response latencies that consumer researchers are accustomed to, in which slower responses in brand recognition tasks are taken to reflect weaker memory traces rather than additional processing (Herr, Farquhar, and Fazio 1996). Also note that the fine temporal resolution of single-neuron analysis allows for the study of the *formation* of category (and brand) associations, not just the outcomes of this process.

Sensory Discrimination

Consumers' preference for one product over another often depends on perceiving differences between them using the senses of sight, touch, taste, smell, or hearing (Krishna 2012). Examples include the brightness of a computer monitor, the softness of washed clothes, and the taste and smell of wine. Firms attempting to identify worthwhile product improvements over competing products or their own existing products often need to determine whether consumers can discriminate between different versions. Single-neuron research has found that neural sensory discrimination can sometimes exceed conscious sensory discrimination, implying that some product improvements may affect sensory perception outside conscious awareness.

For example, neurons identified in the auditory cortex responded selectively to particular sound frequencies, with selectivity bands varying between one-sixth and one-eighteenth of an octave (Bitterman et al. 2008). The narrow-

est of these bandwidths indicate neural sensory discrimination that exceeds the discrimination that most humans display in hearing tests. In addition, different neurons respond to "natural" sounds, as represented by the acoustic instruments, versus artificially generated sounds. Further research could explore whether subconscious sensory discrimination at the neural level can affect overall product evaluations and how this impact may differ from what happens when discrimination operates at a conscious level.

Reactions to Novel Versus Familiar Stimuli

Feelings of novelty and familiarity can have powerful influences on consumers' decisions. On the one hand, consumers pursue novelty to obtain variety or stimulation (e.g., Kim and Drolet 2003; Raju 1980). On the other hand, they tend to evaluate more familiar products and brand logos more favorably because of increased processing fluency (Janiszewski and Meyvis 2001; Shapiro 1999). However, whereas it is rather straightforward to assess how differences in prior exposure influence consumer evaluations, it is more challenging to measure the feelings of novelty or fluency that are assumed to mediate these effects. Furthermore, it is not clear whether novelty and familiarity effects are opposite sides of the same mechanism or possibly orthogonal processes. Single-neuron research can be used to track these underlying mechanisms, and it has already provided some surprising insights into the lasting effects of one-time exposures.

The firing rates of neurons in the hippocampus and amygdala increased selectively in response to visual images that either were being viewed for the first time (novelty neurons) or had been viewed previously (familiarity neurons) (Rutishauser, Mamelak, and Schuman 2006). These novelty and familiarity neurons were often very close to each other in the brain, sometimes in close proximity to the same microwire probe. This research also found that the firing rates of these neurons on subsequent exposures did not change between 30 minutes and 24 hours after the first exposure. This temporal stability in firing rates suggests that the encoding of the familiarity neurons represents a form of long-term memory for stimuli, rather than a short-term priming or habituation effect.

Rutishauser, Mamelak, and Schuman (2006) also developed a classification model to predict whether a stimulus was novel or familiar, based solely on the firing rate of a single neuron. Predictive accuracy was 67%, which was well above chance. The model's accuracy increased to 93% when firing rates were aggregated across six simultaneously recorded neurons that had been assigned to the same type (novelty or familiarity). Finally, participants' neuronal coding of an image as novel versus familiar was accurate even when they performed no better than chance when verbally recalling which screen quadrant that image appeared in when they first viewed it. The authors propose that this result indicates that successful recollection of an episode in memory—in this case, recollection of the circumstances of the first exposure to an image—is not necessary to prompt a familiarity response in neurons. Further research could explore whether these neural familiarity responses can improve predictions of judgments and behaviors over predictions based solely on explicit recollections.

Moreover, the study of familiarity neurons could potentially aid in further specifying conceptual models of phenomena that interest marketers and consumer researchers. One such issue is the distinction between instances when consumers consciously “remember” a specific episode (e.g., a product in an advertisement) and instances when they only “know” that something is familiar (e.g., they know that they have seen a product before but do not remember where). Single-neuron research could contribute to the ongoing debate (Wixted 2007) about whether these two types of judgments rely on qualitatively different mechanisms (e.g., different familiarity neurons responding for remembering versus knowing) or, instead, are a function of quantitative differences in memory strength (e.g., the same familiarity neurons firing at greater rates for remembering versus knowing). Another conceptual area that could benefit from studying familiarity neurons is the nature of processing fluency. Research suggests that different types of fluency (conceptual, perceptual, and linguistic fluency) all act through the same underlying process because their effects on judgments are highly similar (Alter and Oppenheimer 2009). If familiarity neurons respond similarly to different fluency manipulations, this would provide direct evidence of this unifying theory. For example, because priming consumers with the word “frog” can increase their choice of a wine with a frog on the label by enhancing its perceptual fluency (Labroo, Dhar, and Schwarz 2008), researchers could examine whether this verbal prime increases the firing of familiarity neurons on viewing the label or works through another mechanism instead.

Recalling Experiences

Whether and how consumers recall past experiences has a critical impact on their judgments and decisions. Customers’ satisfaction is mostly determined by their recollection of the consumption experience. Similarly, television commercials will only influence consumers at the point of purchase if consumers can explicitly or implicitly recall elements from the commercial. However, recalling experiences is far from straightforward. Rather than being fully recalled, experiences are often reconstructed from key elements, such as the peak and end of a television commercial (Baumgartner, Sujan, and Padgett 1997). Moreover, the recall of experiences is often influenced by the encoding context, leading to recommendations to coordinate advertising and product packaging (Garretson and Burton 2005). Single-neuron research has confirmed this link between encoding and retrieval and opens up the possibility of analyzing the time course of experience reconstruction from memory.

Gelbard-Sagiv et al. (2008) show that neurons in the hippocampus and entorhinal cortex increased their firing rates both when participants first viewed short film clips and when they later freely recalled those clips. Thus, these neurons provide a link between memory formation and recall (Fried et al. 2014). The firing rates increased well before the verbal report of recall started (approximately 1.5 seconds earlier), suggesting that the feeling of knowing may precede actual awareness of knowing. Increased activity remained even after verbal reporting of the recall ended, and took approximately 10 seconds to return to the baseline level of activity. Some neurons responded to more than one video clip—the

average was 1.4 clips per responsive neuron—such as responding to episodes of both *The Simpsons* and *Seinfeld*, implying that such clips may be related on the basis of an abstract association rule (e.g., both are comedies).

These findings also suggest a future research direction. If it is possible to identify neurons that are activated during the encoding of specific parts of the experience (e.g., corresponding to the peak, trough, or end moments of the experience), it should also be possible to monitor the activity in these neurons during recall. This pattern of activity could then be used to examine how consumers use specific elements to reconstruct their past consumption experiences, such as which parts of the experience they (implicitly) recall and in what order. Note that this approach could also be used to examine preference construction, similarly capitalizing on the high temporal resolution of single-neuron research. Researchers could measure the order in which consumers access different parts of information while deliberating on a choice and then connect the timing and extent of activation of these elements with consumers’ decision outcomes.

Finally, another area in which single-neuron research could open up new avenues for consumer research is that of conscious regulation of thoughts and emotions. It is in this area that we detail an example of single-neuron research to illustrate the procedure, including not only its possibilities and potential but also its limitations.

ILLUSTRATIVE EXAMPLE: UP-REGULATION OF FEAR

Background

Marketers often try to motivate consumers to suppress or enhance thoughts and responses. For example, a conservation group might show people an image of a thriving rain forest and ask them to imagine how they would feel if the life and diversity of the rain forest disappeared. Or a public health organization might try to persuade people to resist thoughts about consuming tasty but unhealthy foods by focusing on less tasty but more healthful alternatives. Consumers also might want to control their responses to products and services even without motivation from marketers, such as enhancing (or reducing) their fear while watching a scary movie or riding on a roller coaster or controlling their sadness while listening to moody pop songs. In other cases, consumers might believe that controlling their responses could help them exert self-control by resisting momentary temptations, such as suppressing excitement about dessert options and instead focusing on the negative consequences of weight gain, enhancing their fear of deteriorating health if they want to quit smoking, and focusing on the car attributes of safety and mileage rather than getting carried away by the car’s power and styling.

To illustrate how single-neuron research is conducted and how data are analyzed, we examine whether people can willfully up-regulate (i.e., enhance) their level of fear in response to visual stimuli and whether we can observe that process at the level of single-neuron activity. We use reactions to videos—stimuli that are not often used in single-neuron research—because they are commonly used in marketing communications depicting fear appeals. We also compare people’s ability to enhance fear across two stimuli. One stimulus tends to automatically evoke substantial fear

(a video of a spider) and one does not automatically evoke much fear but has the potential to do so upon elaboration (a video of Al Gore discussing the consequences of climate change).

This investigation adds to prior consumer research on the persuasive effects of communication campaigns designed to arouse fear (Keller and Block 1996). Such fear appeals typically describe the negative consequences of what will happen if some message is not heeded (Witte 1992). Organizations that use fear appeals hope that when people view the messages, they will elaborate on them, causing increased feelings of fear and, in turn, motivating changes in behavior. Although high levels of fear can sometimes lead to defensive processing, which can limit persuasion, Keller and Block (1996) find that for communications that inherently have low levels of fear, increasing elaboration of the message leads to increased effectiveness. Thus, a relevant question is whether people who view a fear communication can regulate their fear in an upward direction when processing the message and, if so, whether this ability varies depending on the nature of the fear-inducing stimuli.

Most prior research on the regulation of emotions has focused on how people *reduce* negative emotions, a process known as “down-regulation” (Goldin et al. 2008). In this area, research has distinguished between behavioral regulation, in which the feelings are still present but action based on those feelings is limited, and more cognitive approaches, in which the feelings themselves are reduced (Gross 2002). Moreover, people tend to employ different strategies to reduce their feelings. One strategy is to purposely avoid paying attention to emotional stimuli to limit their impact. Another, alternative approach is to use higher-order cognitive processes to reinterpret, or reappraise, the meaning of a stimulus as a way to change the emotional response to it (Ochsner and Gross 2005). Although imaging research has begun examining regions of the brain involved in emotion regulation, limited data and differences across studies hinder current ability to fully understand what brain systems are involved in emotion regulation (Ochsner and Gross 2005). Some neural research has examined how people down-regulate the specific emotion of fear (for a review, see Hartley and Phelps 2010). That research has examined the different ways people can down-regulate fear; however, while the brain regions associated with fear regulation are beginning to be uncovered, many of the insights come from studies with nonhuman animals.

In comparison with down-regulation, less attention has been given to the “up-regulation” of emotions, including people’s ability to voluntarily increase their actual feelings, the processes involved, and their neural bases. As a notable exception, Ochsner et al. (2004) use fMRI to investigate both up- and down-regulation of negative emotions when viewing aversive images. Specifically, they examined which neural regions were involved for up- versus down-regulation and for different regulatory strategies. However, prior research has not examined up-regulation of specific emotions, as opposed to negative emotions in general, because standard neural methods usually cannot reliably identify these. By contrast, the single-neuron approach, which can identify neurons that respond to very specific neural tasks, has the potential to identify neural activity

associated with specific emotions. Thus, up-regulation, or enhancement, of fear is the focus of our empirical illustration of single-neuron research because the issue of fear in communications is of interest to marketers and consumer researchers and because it is a question that other neural methods, such as fMRI, are less able to examine.

Fear appeals in marketing communications emphasize a wide variety of outcomes. One way these outcomes vary is in their tendency to automatically create fear in the absence of elaboration. Whereas some outcomes create substantial fear without the need for elaboration (e.g., severe bodily injury due to drunk driving), others tend to naturally elicit relatively little fear but could potentially do so upon elaboration (e.g., high blood pressure resulting from an unhealthy diet). In the latter case, marketers may want to know whether motivating consumers to voluntarily enhance their fear for this outcome, which does not naturally evoke much fear, could be effective. Therefore, in the example study presented here, we use two videos that vary in whether they automatically evoke substantial fear.

Single-Neuron Research for Studying Fear Regulation

Single-neuron research offers a unique opportunity to study consumers’ actual ability to control their thoughts and emotions. Like other neuroscience methods, it avoids the potential demand effect issues of self-reports. In addition, the single-neuron method can detect the immediate activation of specific thoughts and emotions in response to a stimulus, with a temporal resolution of less than one ten-thousandth of a second.

Single-neuron studies in humans have examined people’s ability to regulate their thoughts. Cerf et al. (2010) identify neurons in the hippocampus, amygdala, entorhinal cortex, and parahippocampal cortex, whose firing rates increased when participants viewed one of two specific visual images, but not for the other image. Participants then saw both images and were asked to enhance thinking of one (the target image) and to suppress thinking of the other (the distractor image). Participants were aided with feedback: as the neurons associated with a particular image became more active, that image became less transparent on the screen. On average, participants were able to succeed at this task more than 70% of the time. In most of these success trials, the firing rates of neurons associated with the target image increased, and the firing rates of neurons associated with the distractor image decreased. Note that if some neurons increase in firing rates and others decrease during thought regulation, the result could be that total neural activity and, thus, demand for oxygen in a relatively small region do not change, so these regulation effects would be difficult to detect with fMRI.

Although this prior research has shown that people can control the firing of neurons associated with specific *thoughts*, no single-neuron research has examined how firing rates change with an attempt to regulate emotions. The study we describe herein is an initial exploration of the up-regulation of fear. We specifically examine whether people can enhance their reaction to fearful imagery by willfully increasing their actual fear (rather than by adjusting their behavioral response or by increasing their feelings through selective attention and exposure). Furthermore, we do so for

both a video that naturally evokes substantial fear and one that does not evoke much fear but has the potential to do so upon elaboration.

Methodology: Overview of Stages and Objectives

In Stage 1 of the procedure, we recorded participants' neural activity while they viewed still images intended to evoke different emotions. We used these data to identify neurons that responded selectively to fear. Such initial tasks are commonly used in single-neuron research to identify neurons that respond selectively to a particular type of stimulus. In Stage 2, participants were exposed to the experimental stimuli of interest: they watched each of the two videos, with and without instructions to enhance their emotions.

The data analysis is typical of single-neuron research and relies on methods that are widely accepted in single-neuron literature. In Stage 1, we identify signals from individual neurons, which involves separating neural firing signals from the background signal and separating individual neurons whose firings are recorded on the same microwire, as sometimes happens. We then establish a baseline firing rate for each neuron, after which we identify periods when the neuron is firing at a significantly higher rate than baseline. Finally, we identify neurons whose firing rates respond selectively to the fearful images presented in the initial task. In Stage 2, we test within-subject how firing rates for those fear-responsive neurons differ between the experimental conditions: for each of the two videos and for natural viewing versus viewing with enhanced emotions.

Stage 1: Exposure to Emotion-Evoking Images

Eight participants took part in the study. All were patients who had pharmacologically intractable epilepsy and who had undergone neural probe implantation for clinical purposes, to identify the seizure foci (for detailed description of the implantation procedure, see Fried et al. 2014). The experiment consisted of two stages, during which participants sat in front of a laptop computer in their hospital room while connected to equipment that constantly monitored signals from their neural probes. The laptop and the signal monitor were synchronized to a common clock accurate to within microseconds.

In Stage 1, participants viewed both still images chosen in advance to prompt different specific emotions, including fear, disgust, anger, sadness, surprise, and happiness, and neutral images. Images were chosen in two ways. First, a set of images, common across all participants, was chosen from the International Affective Picture System (IAPS), a collection of images designed to induce different emotions (Lang, Bradley, and Cuthbert 1999). Although the IAPS images were originally developed to prompt negative or positive emotions (Lang, Bradley, and Cuthbert 1999) with varying levels of arousal, subsequent researchers have found that many IAPS images prompt one particular emotion or only two or three specific emotions (Mikels et al. 2005). Second, for each participant, a smaller set of images was chosen on the basis of initial interviews between that participant and one of the authors, in which participants were asked to name objects or experiences that prompted particular emotions for them. The

corresponding images were then chosen either from the IAPS set or, if no such image was available, from images found online. Prior single-neuron research has used this customized approach to choosing images or stimuli particularly relevant to a participant (e.g., Quian Quiroga et al. 2005). The total number of images per participant varied from 30 to approximately 60, depending on the time available with the participant. Each participant saw each image four times in a session, and some participants completed more than one session, depending on how long they stayed in the clinic before surgery. Responses from each participant were then rapidly analyzed to identify which, if any, of the individual neurons detected by the probes changed their activity (i.e., firing rate) compared with the baseline, in response to images associated with a specific emotion. The analysis used to identify these neurons, which we describe subsequently, is similar to that used in prior research (Cerf et al. 2010; Mormann et al. 2011).

Note that the first author conducted Stage 1 as part of an independent single-neuron study. It is common practice for single-neuron researchers to share patient-specific data, so that each research team can make the best use of the limited time available with these participants. Thus, in this study, the data on reactions to the still images are common across teams, while the data and stimuli used in Stage 2 are unique to our study.

Stage 2: Exposure to Video Clips

In Stage 2, participants viewed a set of video clips. Depending on their willingness and ability to continue, they viewed between four and eight video clips associated with different emotions. We focus on two video clips associated with the specific emotion of fear that all participants viewed. One clip was likely to automatically create substantial fear. It lasted for 190 seconds and depicted a large spider crawling toward the camera, with its features showing at a high level of detail. The second video clip was unlikely to automatically induce substantial fear but had the potential to do so upon elaboration. The clip came from Al Gore's film *An Inconvenient Truth* and lasted for 310 seconds. It showed Gore speaking on climate change, followed by footage of disaster zones in Louisiana following Hurricane Katrina. Note that these clips differ in many ways other than the amount of fear they naturally evoke, including how arousing they are, so any inferences about observed differences in neural responsiveness are tentative.

We instructed participants to view the clips with one of two objectives in mind: (1) watch with natural feeling and (2) try to enhance their emotions (i.e., up-regulate). Thus, we used a 2 (instructions) \times 2 (video clip) within-subject design. The order of these four experimental cells for each participant was determined randomly. Participants viewed both video clips in both conditions multiple times. The number of times each participant cycled through all four combinations varied depending on differences in participants' availability, clinical considerations, the amount of time they wanted to devote to studies, and the length of their observation period before surgery. Table 2 provides the number of cycles per participant.

After participants viewed the video clips, during the debriefing, we asked them to describe the strategies they

Table 2
INFORMATION ABOUT PARTICIPANTS AND NEURONS

	Participant								Average Across Neurons (SD)
	1	2	3	4	5	6	7	8	
Number of experimental sessions	1	2	1	1	1	1	1	1	
Number of viewings of each video clip within each condition	8	5	5	5	4	4	2	3	
Number of microwires implanted	80	96	80	96	96	64	64	80	
Electrode locations	[R ^a /L ^a] Am, [R/L] Hipp, [R/L] EC, [R/L] PHC, [R/L] OFC	[R ^a /L ^a] Am, [R/L] Hipp, [R/L] EC, [R/L] PHC, [R/L ^a] OFC	[R ^a /L] Am, [R/L] Hipp, [R/L] EC, [R/L] PHC, [R/L ^a] OFC	[R ^a /L] Am, [R/L] Hipp, [R/L] EC, [R/L] PHC, [R/L] OFC	[R/L] Am, [R/L] Hipp, [R/L] EC, [R/L] PHC, [R ^a /L ^a] OFC	[R ^a /L] Am, [R/L] Hipp, [R/L] EC, [R/L] OFC	[R] Am, [R] EC, [R/L] Hipp, [R] PHC, [R] STG, [R ^a /L ^a] OFC	[R/L ^a] Am, [R/L] Hipp, [R/L] EC, [R/L] PHC, [R/L] OFC	
Number of neuron units detected	22	37	27	8	17	7	7	3	
Number of fear-responsive neurons	8	6	8	3	3	1	2	2	
<i>Mean Firing Rates of Fear-Responsive Neurons (Hz)</i>									
Baseline	1.1	.8	.2	.6	.6	3.0	2.1	.7	1.1 (.9)
Fearful images (part 1)	7.7	12.1	20.0	16.2	12.4	7.2	8.5	18.8	12.9 (5.0)
Spider: natural	7.0	9.3	17.4	15.1	10.0	5.8	5.9	15.8	10.8 (4.7)
Spider: enhanced	7.4	10.5	16.4	15.2	10.9	5.3	6.3	17.1	11.1 (4.7)
Climate change: natural	2.3	2.3	1.2	.3	.5	4.0	2.3	.9	1.7 (1.2)
Climate change: enhanced	4.1	4.8	6.8	13.3	5.0	3.1	5.3	3.0	5.7 (3.3)

^aFear-responsive neuron detected in this area.

Notes: [R/L] Am = amygdala; Hipp = hippocampus; EC = entorhinal cortex; PHC = parahippocampal cortex; OFC = orbitofrontal cortex; STG = superior temporal gyrus

used to enhance their fear level while watching the video clips. We also asked them about their general attitude toward climate change to verify their general understanding of this issue.

Stage 1 Analysis and Results: Identification of Fear-Responsive Neurons

After each of the two experimental parts, we analyzed the data offline (i.e., outside the participant's room). Note that this approach differs from some single-neuron research in which analyses take place in real time and the findings are immediately used to determine what happens next in the experimental session (Cerf et al. 2010). The general approach we used to identify neurons and neuron spikes follows the algorithm set out by Quian Quiroga, Nadasdy, and Ben-Shaul (2004) and is typical of single-neuron research.

Identifying signals from individual neurons. First, we used a high-pass filter to remove background activity from neurons that were too far away to produce detectable spikes. We identified individual spikes to separate local noise from spiking activity. A signal was defined as a spike candidate if

the peak signal was at least .675 standard deviations above the median signal coming from that particular microwire. Following this filtering, we removed spikes whose properties either were too rapid (i.e., less than 3 milliseconds apart) or had too high an amplitude (greater than 50 SDs of the mean signal from the wire). These signals are typically artifacts generated by, for example, the participant's head movement.

Second, we separated signals from different neurons that were detected on the same microwire, a process known as spike sorting. Prior electrophysiology studies (e.g., Wehr and Laurent 1996) have shown that separating spikes from individual neurons can be crucial to understanding the coding of the brain, because the brain often aggregates information from the activity of multiple neurons that encode different features of stimuli or cognitive activities. Some of the microwires do not pick up distinct firing spikes from any neurons and only carry background activity. Other wires detect spikes from only one neuron, which can be readily checked by using the algorithm to ensure that the firing pattern is the same for each spike. These neurons are called "single units." However, some wires pick up two or

more distinct firing signatures, indicating that the wire is physically close to multiple neurons. In these cases, the firing patterns are examined with a clustering algorithm. Sometimes it is possible to assign each spike to a particular neuron, and these neurons are then also called "single units." However, sometimes it is not possible to discriminate among all neurons recorded on the same microwire, and these wires are then deemed to be recording "multiunits." In human single-neuron research, these multiunits are typically still used for analysis rather than being discarded. This assignment can be done with a high degree of reliability. In what follows, the term "neuron" refers to a single- or a multineuron unit, as identified on a microwire. This terminology has been widely adopted in human single-neuron research.

The 656 total microwires detected 128 neuron units. Details for each patient, including the locations of these neurons, appear in Table 2. An average of 16.0 (SD = 11.9) distinct neurons were recorded per participant, with a range from 3 to 37. Note that sometimes a neuron's signal can decay during the course of a study with multiple sessions, due to slight shifting of the microwire, a seizure, or changes in the tissue surrounding the microwire.

Estimating a baseline firing rate for each neuron. The next step was to identify a baseline firing rate for each neuron. Most neurons produce spikes even when they are not responding to particular stimuli, but rather continuing firing at a baseline rate. For each neuron, we defined the baseline rate as either its firing rate for a one-minute interval before the participant was exposed to any experimental stimuli or its average firing rate during one-half-second intervals during viewing when only a small cross appeared in the screen's center. Note that these two measures tend to yield the same results (Cerf et al. 2010). These baseline rates were typically .1–3 Hz.

Identifying responsive periods for each neuron. Next, we searched for periods when a neuron was active, relative to the baseline. We deemed a neuron to have increased activity (also called "excitation") during a particular time interval if the firing rate in that interval increased by at least 5 standard deviations above the baseline firing rate for that neuron, and we deemed it to have decreased activity (inhibition) if the firing rate decreased by at least 2 standard deviations, but only if the median number of spikes observed during the baseline monitoring period was at least two. These definitions are consistent with prior single-neuron research (e.g., Cerf et al. 2010; Mormann et al. 2011).

Identifying neurons that respond to fear. The next step was to identify neurons whose activity increased or decreased when a participant was observing a fear-evoking image in Stage 1 of the experiment. In particular, we looked for changed activity from 300 milliseconds until 5 seconds after the fearful stimulus appeared on the screen, or until the activity burst decayed back to baseline, because neural response to a visual stimulus can continue even after the stimulus is removed from sight (Gelbard-Sagiv et al. 2008). We classified neurons as responsive when, throughout the exposure to the fearful stimulus, their firing rate increased by more than 5 standard deviations above the baseline rate. Using this procedure, of the 128 identified neurons, we categorized 33 as fearful, 14 as a negative emotion other

than fear (e.g., anger, disgust, sadness), and 51 as responding to a positive emotion. The remaining 30 did not respond to positive or negative emotions, based on the reaction to the IAPS images. For the neurons categorized as responding to fear, the mean firing rate at baseline was 1.1 Hz (SD = .9), and the mean rate when viewing a fearful image was 12.9 Hz (SD = 5.0; for details, see Table 2).

Note that these criteria for determining responsiveness are different from those typically used in imaging experiments, such as fMRI, which measures a blood oxygen level-dependent signal of neural activity in a population of tens of thousands or up to millions of neurons. Aside from relying on spatial aggregation, the blood oxygen level-dependent signal relies on slower hemodynamic changes, on the order of seconds, rather than the submillisecond sensitivity of the single-neuron monitoring. With these differences, the electrophysiological analysis in single-neuron research is a more direct measure of neural activity, which allows for a more straightforward presentation and interpretation of the data. Thus, whereas in fMRI the analyst must apply a statistical criterion to the signal, which results in a significance value "heat map" of the brain, in single-neuron research, the analyst can typically present the raw data after identifying spikes. That is, the results are typically depicted using a visualization of the spiking event over time.

Next, we tested (1) whether these fear-responsive neurons were more responsive to fear than to other negative emotions and (2) whether these fear-responsive neurons responded more strongly to the fearful images than the neurons categorized with the other negative emotions. First, across all participants, all relevant neurons, and all viewings of the relevant IAPS images, the mean firing rate for the fear-responsive neurons was significantly higher when participants viewed the fearful images ($M = 6.4$ Hz, $SD = 6.2$ Hz, $n = 4,312$) than when they viewed images associated with other negative emotions ($M = 3.8$ Hz, $SD = 3.9$ Hz, $n = 736$; $Z = 9.64$, $p < 10^{-21}$, Wilcoxon rank-sum). Second, the mean firing rate for neurons associated with negative emotions other than fear, when participants viewed fearful images ($M = 5.1$ Hz, $SD = 2.7$ Hz, $n = 2,168$), was significantly lower than the corresponding firing rate for fear-responsive neurons ($Z = 2.06$, $p = .03$, Wilcoxon rank-sum). Given this pattern of reactions, we label these neurons as fear-responsive, though we cannot rule out that they are responding to related changes, such as an increase in arousal.

Stage 2 Analysis and Results: Effect of Emotion Enhancement on Fear Responses to Video Clips

We next examined whether participants' attempt to enhance their emotional responses to the video clips increased firing rates in their fear-responsive neurons. We determined mean firing rates during viewing of each clip by dividing the total number of spikes during viewing by the length of the clip in seconds.

Firing rates of fear-responsive neurons during natural viewing. We tested whether natural viewing of the spider clip did indeed increase firing rates of the fear-responsive neurons compared with the baseline and with natural viewing of the climate change clip. The mean firing rate for fear-responsive neurons during natural viewing of the spider clip

($M = 10.8$ Hz, $SD = 4.7$) was significantly higher than the baseline firing rate ($M = 1.1$ Hz, $SD = .9$; $Z = 3.31$, $p < .0001$, Wilcoxon rank-sum) and not significantly different from their mean firing rate during exposure to the fearful IAPS images in Stage 1 ($M = 12.9$ Hz, $SD = 5.0$; $Z = -.99$, n.s., Wilcoxon rank-sum). Furthermore, the mean firing rate during natural viewing of the climate change clip ($M = 1.7$ Hz, $SD = 1.2$) was not significantly different from the baseline rate ($Z = 1.00$, n.s., Wilcoxon rank-sum) and was significantly lower than the mean firing rate during exposure to the fearful IAPS images ($Z = -3.31$, $p < .001$, Wilcoxon rank-sum) and during viewing of the spider clip ($Z = -3.31$, $p = .01$, Wilcoxon rank-sum). In summary, this analysis confirms our assumption that the spider clip naturally creates substantial fear (similar to the fearful IAPS images) whereas the climate change clip does not.

Firing rates of fear-responsive neurons during emotion enhancement. Next, we examined whether the firing rates of fear-responsive neurons increased when participants were instructed to enhance their emotions while viewing the clip. The mean firing rate during viewing of the climate change clip was significantly higher in the enhanced emotion condition ($M = 5.7$ Hz, $SD = 3.3$) than in the natural viewing condition ($M = 1.7$ Hz, $SD = 1.2$; $Z = 3.10$, $p < .001$, Wilcoxon rank-sum). In contrast, the mean firing rate during viewing of the spider clip did not differ significantly between the enhanced emotion condition (11.1 Hz, $SD = 4.7$) and the natural viewing condition ($M = 10.8$ Hz, $SD = 4.7$, $Z = .26$, n.s., Wilcoxon rank-sum). Note that, even during enhanced viewing of the climate change clip, the mean firing rate was still significantly lower than that during natural viewing of the spider clip ($Z = -2.57$, $p = .01$, Wilcoxon rank-sum).

Figure 2 depicts an example of the impact of emotion enhancement for one neuron of one participant viewing the climate change clip. This neuron had a 1.1 Hz baseline firing rate, increasing to an average of 12.0 Hz when the participant viewed fearful images in Stage 1. In Stage 2, during the climate change clip, the firing rates for this participant were 2.1 Hz during natural viewing and 5.3 Hz in the enhanced emotion condition.

Test for changes in firing rate over repeated viewings. We also examined how neural activity changed across multiple viewings of the same video clip. It is possible that the fearful nature of a clip, or the effectiveness of emotion enhancement, can either increase or decrease over repeated viewings. When testing the change in neural activity over repeated exposures to the same video in the natural viewing condition, we observed that the change in activity, though positive, was quite small across trials ($M = .1$ Hz, $SD = 1.9$; $p = .02$, Wilcoxon rank-sum comparing the change in the original set with that of 1,000 randomly shuffled sets of trials selected from the same data using bootstrapping). Thus, in this particular context, the fear response to a video clip was influenced more by willful regulation than by repeated exposure.

Test for changes in firing rate of other neurons during enhancement. In addition, we examined whether the enhancement effect observed in the climate change condition was specific to the fear-responsive neurons. Although other neurons also directionally increased their firing rate when participants viewed the climate change clip in the

enhanced condition ($M = 3.0$, $SD = 3.1$ Hz) rather than in the natural viewing condition ($M = 1.7$ Hz, $SD = 1.2$), this difference was only marginally significant ($Z = 1.74$, $p = .08$, Wilcoxon rank-sum) and was significantly smaller than the increase for the fear-responsive neurons ($D_{\text{other}} = 1.3$ Hz, $D_{\text{fear}} = 4.0$ Hz; $Z = 3.43$, $p < .001$, Wilcoxon rank-sum). Thus, the increase observed for the fear-responsive neurons was not due to a general increase in the firing rate of all neurons due to the instructions to enhance emotions. Still, it is possible that these neurons were reacting to something other than fear but were highly correlated with it, such as increased arousal.

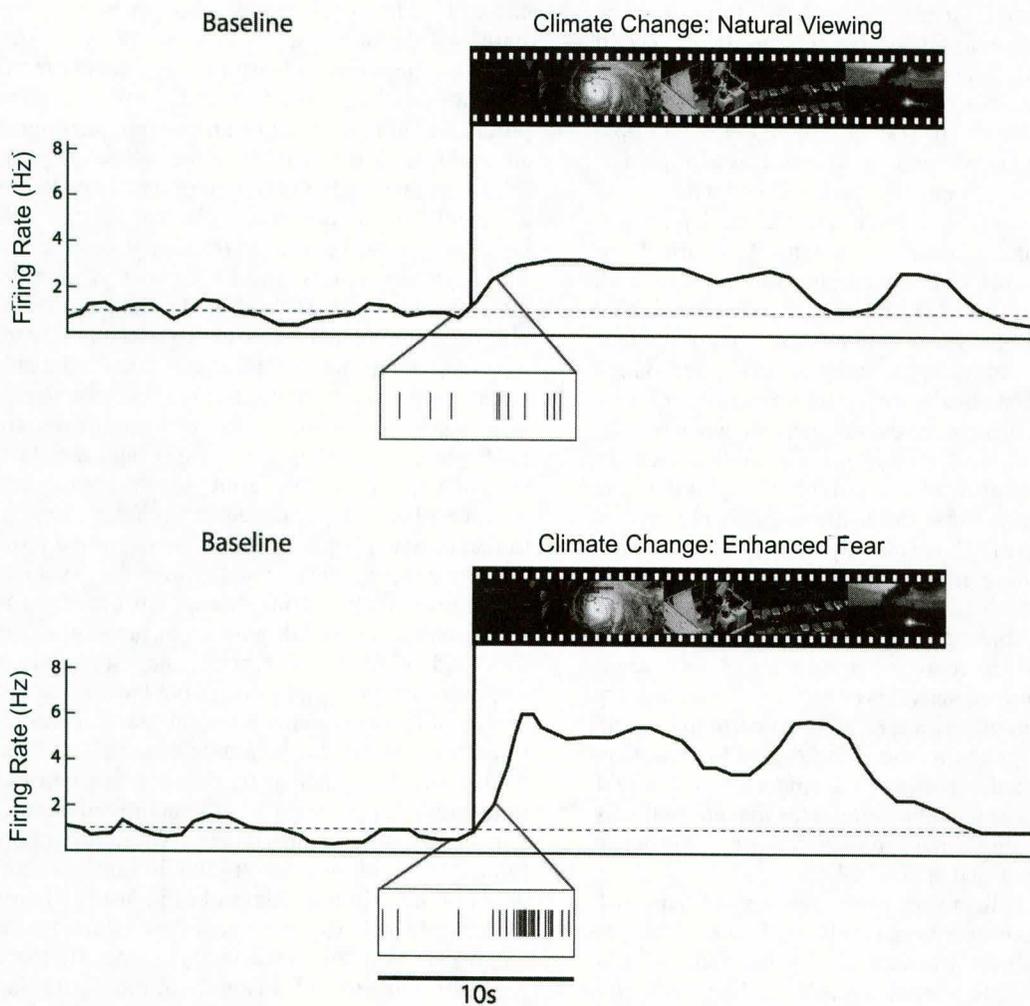
GENERAL DISCUSSION

This article examines the potential of using single-neuron analysis in the human brain to study consumer behavior. Although this methodology is only a decade old, it has matured to the point at which marketers and consumer researchers can not only learn from extant findings but also begin to use this method to obtain important new insights into consumer behavior and decision making, which in turn can complement and augment insights obtained from other market research methods, including other neuroscience approaches.

We first described the general methodology of single-neuron research in humans, after which we discussed its potential advantages and disadvantages and provided an overview of existing single-neuron research and its potential relevance for marketing and consumer behavior. To illustrate how single-neuron research is conducted, we described a study that examines people's ability to voluntarily enhance emotions, focusing on feelings of fear, and used that study both to illustrate how data are collected and analyzed in single-neuron studies and to highlight the issues to be considered and the decisions to be made when using this research method. Although the primary purpose of the study was to introduce to a marketing audience the single-neuron method, its findings offer preliminary insights that can help illustrate the potential of single-neuron research in marketing.

First, the results suggest that for a video clip that does not automatically induce a high level of fear, people can voluntarily enhance the fear they experience. Seven of the eight participants (all but participant 6) were able to willfully increase the firing rate of fear-responsive neurons while watching the climate change clip. In other words, they were able to up-regulate their emotions directly without resorting to changes in behavior, exposure, or attention. This result suggests that when people are motivated to pursue a goal but find doing so difficult (e.g., dieting, quitting smoking, recycling), public service ads could help persuade them to voluntarily increase their experienced fear (e.g., fear of poor health or environmental disaster) and thus bolster their resolve. Second, participants were not able to increase the firing rate of the fear-responsive neurons in response to the spider clip. This suggests that people may not be able to voluntarily increase their experienced fear in response to stimuli that already automatically induce substantial fear. Third, although emotion-enhancing participants could increase their fear response to the climate change clip relative to a natural viewing baseline, the resulting firing rates were still

Figure 2
SINGLE-NEURON FIRING RATE DURING FEAR ENHANCEMENT



Notes: Firing rate for one neuron of one participant viewing the climate change clip under natural viewing ($M = 2.1$ Hz) and under emotion enhancement ($M = 5.3$ Hz). Each vertical line in the enlarged window represents a neuron firing spike.

lower than those of the spider clip when viewed naturally, without enhancement. Thus, there may be limitations in how much people can volitionally increase fear when it is not automatically induced.

These kinds of insights would be difficult to obtain using other methods. Self-reports might be highly susceptible to demand effects or participants' inability to accurately report levels of fear. Facial expressions may not capture subtle fear responses in a video-viewing context or allow for a similar quantification of the degree of fear. Physiological monitoring would have difficulty distinguishing fear from other negative emotions. Even fMRI would have difficulty distinguishing neural activity related to fear from that related to other emotions, because many of the same neural regions show increased activity in response to multiple emotions.

Study Limitations

Some of the limitations of our study help illustrate the more general limitations of the single-neuron approach. We cannot definitively claim that it is fear, and only fear, that increases the firing rate in the fear-responsive neurons. For example, as we noted previously, it is possible that the neurons are responding to a phenomenon that is correlated with fear, such as increased arousal. This general limitation is shared by most neural methods that study responses to specific stimuli, including fMRI or other imaging methods. At any given time, the brain receives and processes numerous stimuli and is involved in multiple tasks. However, we can identify parts of the brain (regions of the brain for fMRI and individual neurons in the current case) that consistently respond to certain stimuli but not to others. In our study, we identified neurons that consistently responded to images

pretested to evoke fear. Moreover, having participants view the videos several times helped establish that the neurons were responding to something inherent to the video-viewing task and not to any unrelated momentary activity.

Although we used a large sample of still images in the first phase to identify fear-responsive neurons, in the second phase, we used only one example each of the videos that either did or did not automatically evoke substantial fear. We opted for two long clips (rather than many short clips) because we did not know how long it would take for participants' emotion enhancement efforts to succeed when viewing a video clip—success might require several viewings and might not occur until later in a viewing. As it turned out, participants were able to enhance emotion quickly, with many successes even on their first attempt, and early in that attempt. Given this result, it would be desirable to replicate our investigation with a larger sample of (shorter) video clips that either automatically evoke substantial fear or not.

Our finding that firing rates did not increase when participants attempted to enhance their emotions while viewing the already fearful spider clip is potentially subject to the alternative explanation that the firing rates during natural viewing of this clip may have already been close to the neurons' firing rate ceiling. In that case, it would be difficult for voluntary enhancement to create a large increase in firing rates. It is also possible that experiencing very high levels of fear does not further increase the firing rates of the neurons we identified but instead activates an entirely different set of neurons. Yet, although ceiling effects are certainly a concern, it should be noted that the firing rate of the fear neurons during enhanced viewing of the spider clip ($M = 11.1$ Hz) is still well below the high firing rates that are routinely observed in other single-neuron research (on the order of 20–30 Hz; see, e.g., Fried et al. 2014).

We also did not collect alternative measures of fear, such as self-reports, or compare the results with those from the single-neuron analysis. Because survey methods are less expensive, are easier to administer, and can be used with a much larger population of participants, it would be helpful to know if they would produce similar results. However, given the limited time available with each participant, it is not possible to administer a large battery of these measures and still have participants view the still images and videos. We also did not examine fear using fMRI, which, as we noted previously, does not have the resolution needed for examining specific emotions.

Our study focused only on the impact of manipulations on neuron firing rates and did not examine downstream effects of interest to marketers, such as whether the emotion enhancement instructions for the climate change clip also resulted in greater message persuasiveness. This would require a survey-based measure of persuasiveness or a task that produces a measure correlated with persuasiveness, unless a neural marker for persuasiveness could be identified using the single-neuron method. Given the small sample size of participants, the sample size of persuasiveness survey responses would have little statistical power. This limitation of having a small number of participants, as opposed to the much larger sample size across all neurons and viewings, is another limitation common to most single-neuron research.

Incidentally, it is important to note one common point of confusion that often arises in discussions of the results of single-neuron studies: the fact that the results are correlational and, as such, are open for interpretation as to the true cause of the neuronal response. Simply put, we show beyond statistical doubt that a cell is more likely to fire when the image on the screen is fearful rather than not fearful. Therefore, we label the cell a "fear neuron." However, this is purely a human labeling of an existing phenomenon in the environment. It is possible that the cell actually codes something else that could not be determined from the set of stimuli employed in our study. We named the cell as such because we observed that all fear images generated enhanced firing. However, this desire by experimenters to label an effect could, at times, lead to the mistake of reducing an observed phenomenon to a mere description that is easy to work with but is not the biological code for the effect.

Other possible limitations, also common to most single-neuron studies in humans, follow from the research's clinical context. All participants were being treated for pharmacologically intractable epilepsy. Evidence has shown, however, that epilepsy patients' neural functioning is similar to that of nonepileptics in multiple cognitive tests (Herman and Seidenberg 2007). In addition, in the psychiatric and IQ evaluations included in patients' clinical treatment, their scores and answers fall within the range of nonepileptics. That said, there are differences in neural patterns among the two populations (e.g., in sleep), but these do not manifest in the situations in which we test our participants. Additional limitations of our work include the small sample size ($n = 8$), the small number of fear-responsive neurons, limited time with each participant, and the limited number of video clips used (as noted previously). These limitations are also typical of single-neuron studies in humans: ethical standards prohibit implanting probes in healthy human brains; the number of probes used, and thus the number of neurons identified, is limited to the number medically required; there are only a handful of hospitals in the world that conduct single-neuron studies on humans; and the time that a given researcher can have with a patient is limited.

Managerial Implications

Our findings have potentially important implications for marketers interested in using fear appeals in consumer communications, such as public service ads. In particular, our results suggest that designing communications to motivate consumers to consciously increase their fear, through overt instructions in the ad, would be an effective method for increasing experienced fear. The increased firing rates of the fear-responsive neurons indicate that consumers, when requested to enhance their emotions, can do so quite readily and successfully. However, our results also indicate that this approach may only be successful for phenomena that do not, on their own, automatically induce high levels of fear.

Implications for Further Research on Fear Appeals and Emotions

Our study directly instructed participants to enhance their emotions. Although this is a reasonable starting point, many communications that use fear appeals simply urge or nudge consumers to "think about" the phenomenon (e.g., a world

with higher sea levels, less food production capacity), with the assumption that this increased elaboration will lead to a higher level of fear. Future work could use a single-neuron methodology to explore how the impact of these subtle strategies compares with that of our more direct approach.

One frequent criticism of fear appeals is that if a communication creates too much fear, consumers may become defensive and either ignore the message or process it in a biased manner to reduce perceived personal risk (Liberman and Chaiken 1992; Sherman and Cohen 2002; Wolburg 2006). In such cases, eliciting a more moderate level of fear might be more effective. It is, however, difficult to assess with standard research methods whether people confronted with extreme messages do experience reduced feelings of fear—or if, instead, the self-reported absence of fear reflects an attempt at defensive self-presentation rather than an actual absence of fear. Single-neuron studies could help investigate this issue by examining whether use of high-fear communications can decrease actual firing rates of fear-responsive neurons. Caution must be used, however, in exposing patients awaiting surgery to messages that create a very high level of fear.

Further research should examine whether communications that instruct viewers to try to enhance their feelings of fear are more persuasive than those that do not or those that elicit high fear on first viewing. Although single-neuron research can help determine whether people can willfully enhance fear, more traditional behavioral methods are necessary to determine whether communications that instruct viewers to enhance fear will be effective. The small sample sizes of single-neuron methods and the need for within-subject experimental designs limit the ability of this method to test the effectiveness of different types of fear appeals on persuasion. However, to address this and other problems, single-neuron recordings can be used to inform the design of subsequent studies that use different methods, such as traditional behavioral experiments.

Further research might also examine which characteristics of the two fear stimuli used here resulted in successful enhancement for the climate change clip but not for the spider clip. We proposed that this difference could be driven by whether the clip automatically evokes substantial fear or, alternatively, could be due to ceiling effects for neural firing rates. Another possibility is that fear of spiders is an innate fear (Poulton and Menzies 2002) that may even be evolutionary in origin, whereas fear of climate change is not (Öhman and Mineka 2001), and only the latter can be enhanced using cognitive elaboration. For example, Phelps et al. (2001) discuss how people can learn to fear a dog just by hearing that it bit another person. Further research could examine whether people have a different ability to enhance fears that are relatively innate rather than learned. Such research would need to assess a larger selection of fear-evoking stimuli than that used in the current study.

Our study did not measure response latencies for neurons and thus did not use this temporal advantage of the single-neuron approach over fMRI. Additional research could examine how response latencies, starting at the time an emotion-causing image appears, differ across neurons that respond to different emotions. Such research might also examine whether intentionally enhancing emotions affects these latencies.

Conclusion

This article aimed to introduce to the marketing community the single-neuron methodology in humans. As of this writing, several research hospitals are creating or planning to create facilities to study single-neuron research in humans, and this number is expected to increase in the coming years. Thus, single-neuron research facilities are likely to become more accessible to consumer and market researchers. We hope that this article spurs greater discussion of how single-neuron studies can be used to enhance understanding of topics of fundamental importance to consumer research.

REFERENCES

- Alter, Adam L. and Daniel M. Oppenheimer (2009), "Uniting the Tribes of Fluency to Form a Metacognitive Nation," *Personality and Social Psychology Review*, 13 (3), 219–35.
- Baumgartner, Hans, Mita Sujun, and Dan Padgett (1997), "Patterns of Affective Reactions to Advertisements: The Integration of Moment-to-Moment Responses into Overall Judgments," *Journal of Marketing Research*, 34 (May), 219–32.
- Bitterman, Yael, Roy Mukamel, Rafael Malach, Itzhak Fried, and Israel Nelken (2008), "Ultra-Fine Frequency Tuning Revealed in Single Neurons of Human Auditory Cortex," *Nature*, 451 (10), 197–201.
- Boush, David M. and Barbara Loken (1991), "A Process-Tracing Study of Brand Extension Evaluation," *Journal of Marketing Research*, 28 (February), 16–28.
- Cerf, Moran and Michael Mackay (2011), "Studying Consciousness Using Direct Recording from Single Neurons in the Human Brain," in *Characterizing Consciousness: From Cognition to the Clinic? Research and Perspectives in Neuroscience*, Stanislas Dehaene and Yves Christen, eds. Berlin: Springer, 133–46.
- , Nikhil Thiruvengadam, Florian Mormann, Alexander Kraskov, Rodrigo Quiñero, Christof Koch, et al. (2010), "On-Line, Voluntary Control of Human Temporal Lobe Neurons," *Nature*, 467 (October 28), 1104–1108.
- Driver, Jon and Toemme Noesselt (2008), "Multisensory Interplay Reveals Crossmodal Influences on 'Sensory-Specific' Brain Regions, Neural Responses, and Judgments," *Neuron*, 57 (1), 11–23.
- Fried, Itzhak, Katherine A. Cameron, Sharona Yashar, Raymond Fong, and Jack W. Morrow (2002), "Inhibitory and Excitatory Responses of Single Neurons in the Human Medial Temporal Lobe During Recognition of Faces and Objects," *Cerebral Cortex*, 12 (6), 575–84.
- , Moran Cerf, Ueli Rutishauser, and Gabriel Kreiman (2014), *Single Neurons Studies of the Human Brain*. Cambridge, MA: MIT Press.
- Garretson, Judith A. and Scot Burton (2005), "The Role of Spokescharacters as Advertisement and Package Cues in Integrated Marketing Communications," *Journal of Marketing*, 69 (October), 118–32.
- Gelbard-Sagiv, Hagar, Roy Mukamel, Michal Harel, Rafael Malach, and Itzhak Fried (2008), "Internally Generated Reactivation of Single Neurons in Human Hippocampus During Free Recall," *Science*, 322 (October 3), 96–101.
- Glimcher, Paul W. and Ernst Fehr (2014), *Neuroeconomics: Decision Making and the Brain*, 2nd ed. London: Academic Press.

- Goldin, Philippe R., Kateri McRae, Wiveka Ramel, and James J. Gross (2008), "The Neural Bases of Emotion Regulation: Reappraisal and Suppression of Negative Emotion," *Biological Psychiatry*, 63 (6), 577–86.
- Grill-Spector, Kalanit and Rafael Malach (2001), "fMR Adaptation: A Tool for Studying the Functional Properties of Human Cortical Neurons," *Acta Psychologica*, 107 (1–3), 293–321.
- Gross, James J. (2002), "Emotion Regulation: Affective, Cognitive, and Social Consequences," *Psychophysiology*, 39 (3), 281–91.
- Hartley, Catherine A. and Elizabeth A. Phelps (2010), "Changing Fear: The Neurocircuitry of Emotion Regulation," *Neuropsychopharmacology*, 35 (1), 136–46.
- Hermann, Bruce and Michael Seidenberg (2007), "Epilepsy and Cognition," *Epilepsy Currents*, 7 (1), 1–6.
- Herr, Paul M., Peter H. Farquhar, and Russell H. Fazio (1996), "Impact of Dominance and Relatedness on Brand Extensions," *Journal of Consumer Psychology*, 5 (2), 135–59.
- Janiszewski, Chris and Tom Meyvis (2001), "Effects of Brand Logo Complexity, Repetition, and Spacing on Processing Fluency and Judgment," *Journal of Consumer Research*, 28 (1), 18–31.
- Jenison, Rick L., Antonio Rangel, Hiroyuki Oya, Hiroto Kawasaki, and Matthew A. Howard (2011), "Value Encoding in Single Neurons in the Human Amygdala During Decision Making," *Journal of Neuroscience*, 31 (1), 331–38.
- Kassam, Karrim S., Amanda R. Markey, Vladimir L. Cherkassky, George Loewenstein, and Marcel Adam Just (2013), "Identifying Emotions on the Basis of Neural Activation," *PLOS One*, 8 (6), e66032.
- Keller, Punam Anand and Lauren Goldberg Block (1996), "Increasing the Persuasiveness of Fear Appeals: The Effect of Arousal and Elaboration," *Journal of Consumer Research*, 22 (4), 448–59.
- Kim, Heejung S. and Aimee Drolet (2003), "Choice and Self-Expression: A Cultural Analysis of Variety-Seeking," *Journal of Personality and Social Psychology*, 85 (2), 373–82.
- Kreiman, Gabriel, Christof Koch, and Itzhak Fried (2000), "Category-Specific Visual Responses of Single Neurons in the Human Medial Temporal Lobe," *Nature Neuroscience*, 3 (9), 946–53.
- Krishna, Aradhna (2012), "An Integrative Review of Sensory Marketing: Engaging the Senses to Affect Perception, Judgment and Behavior," *Journal of Consumer Psychology*, 22 (3), 332–51.
- Labroo, Aparna A., Ravi Dhar, and Norbert Schwarz (2008), "Of Frog Wines and Frowning Watches: Semantic Priming, Perceptual Fluency, and Brand Evaluation," *Journal of Consumer Research*, 34 (6), 819–31.
- Lang, Peter J., Margaret M. Bradley, and Bruce N. Cuthbert (1999), "International Affective Picture System (IAPS): Technical Manual and Affective Ratings," Technical Report A-8, Center for Research in Psychophysiology, University of Florida.
- Levy, Dino J. and Paul W. Glimcher (2012), "The Root of All Value: A Neural Common Currency for Choice," *Current Opinion in Neurobiology*, 22 (6), 1027–1038.
- Liberman, Akiva and Shelly Chaiken (1992), "Defensive Processing of Personally Relevant Health Messages," *Personality and Social Psychology Bulletin*, 18 (6), 669–79.
- Loken, Barbara (2006), "Consumer Psychology: Categorization, Inferences, Affect, and Persuasion," *Annual Review of Psychology*, 57, 453–85.
- Mikels, Joseph A., Barbara L. Fredrickson, Gregory R. Larkin, Casey M. Lindberg, Sam J. Maglio, and Patricia A. Reuter-Lorenz (2005), "Emotional Category Data on Images from the International Affective Picture System," *Behavior Research Methods*, 37 (4), 626–30.
- Mormann, Florian, Julien Dubois, Simon Kornblith, Milica Milosavljevic, Moran Cerf, Matias Ison, et al. (2011), "A Category-Specific Response to Animals in the Right Human Amygdala," *Nature Neuroscience*, 14 (10), 1247–49.
- , Simon Kornblith, Rodrigo Quian Quiroga, Alexander Kraskov, Moran Cerf, Itzhak Fried, and Christof Koch (2008), "Latency and Selectivity of Single Neurons Indicate Hierarchical Processing in the Human Medial Temporal Lobe," *Journal of Neuroscience*, 28 (36), 8865–72.
- Mukamel, Roy and Itzhak Fried (2012), "Human Intracranial Recordings and Cognitive Neuroscience," *Annual Review of Psychology*, 63, 551–37.
- Ochsner, Kevin N. and James J. Gross (2005), "The Cognitive Control of Emotion," *Trends in Cognitive Sciences*, 9 (5), 242–49.
- , Rebecca D. Ray, Jeffrey C. Cooper, Elaine R. Robertson, Sita Chopra, John D.E. Gabrieli, and James J. Gross (2004), "For Better or For Worse: Neural Systems Supporting the Cognitive Down- and Up-Regulation of Negative Emotion," *NeuroImage*, 23 (2), 483–99.
- Öhman, Arne and Susan Mineka (2001), "Fears, Phobias, and Preparedness: Toward and Evolved Module of Fear and Fear Learning," *Psychological Review*, 108 (3), 483–522.
- Phan, K. Luan, Tor Wagner, Stephan F. Taylor, and Israel Liberzon (2002), "Functional Neuroanatomy of Emotion: A Meta-Analysis of Emotion Activation Studies in PET and fMRI," *NeuroImage*, 16 (2), 331–48.
- Phelps, Elizabeth A., Kevin J. O'Connor, J. Christopher Gatenby, John C. Gore, Christian Grillon, and Michael Davis (2001), "Activation of the Left Amygdala to a Cognitive Representation of Fear," *Nature Neuroscience*, 4 (4), 437–41.
- Plassmann, Hilke, Thomas Zoëga Ramsøy, and Milica Milosavljevic (2012), "Branding the Brain: A Critical Review and Outlook," *Journal of Consumer Psychology*, 22 (1), 18–36.
- Poulton, Richie and Ross G. Menzies (2002), "Fears Born and Bred: Toward a More Inclusive Theory of Fear Acquisition," *Behavior Research and Therapy*, 40 (2), 197–208.
- Prabhakaran, V., K. Narayanan, Z. Shao, and J.D.E. Gabrieli (2000), "Integration of Diverse Information in Working Memory Within the Frontal Lobe," *Nature Neuroscience*, 3 (1), 85–90.
- Quian Quiroga, Rodrigo, Zoltan Nadasdy, and Yoram Ben-Shaul (2004), "Unsupervised Spike Detection and Sorting with Wavelets and Superparamagnetic Clustering," *Neural Computation*, 16 (8), 1661–87.
- , Leila Reddy, Gabriel Kreiman, Christof Koch, and Itzhak Fried (2005), "Invariant Visual Representation by Single Neurons in the Human Brain," *Nature*, 435 (23), 1102–1107.
- Raju, P.S. (1980), "Optimum Stimulation Level: Its Relationship to Personality, Demographics, and Exploratory Behavior," *Journal of Consumer Research*, 7 (3), 272–82.
- Rutishauser, Ueli, Adam N. Mamelak, and Erin M. Schuman (2006), "Single-Trial Learning of Novel Stimuli by Individual Neurons of the Human Hippocampus-Amygdala Complex," *Neuron*, 49 (March 16), 805–813.
- Sanfey, Alan G., James K. Rilling, Jessica A. Aronson, Leigh E. Nystrom, and Jonathan D. Cohen (2003), "The Neural Basis of Economic Decision-Making in the Ultimatum Game," *Science*, 300 (5626), 1755–58.

- Shadlen, Michael N. and Roazbeh Kiani (2013), "Decision Making as a Window on Cognition," *Neuron*, 80 (3), 791–806.
- Shapiro, Stewart (1999), "When an Ad's Influence Is Beyond Our Conscious Control: Perceptual and Conceptual Fluency Effects Caused by Incidental Ad Exposure," *Journal of Consumer Research*, 26 (1), 16–36.
- Sherman, David K. and Geoffrey L. Cohen (2002), "Accepting Threatening Information: Self-Affirmation and Reduction of Defensive Biases," *Current Directions in Psychological Science*, 11 (4), 119–23.
- Waydo, Stephen, Alexander Kraskov, Rodrigo Quian Quiroga, Itzhak Fried, and Christof Koch (2006), "Sparse Representation in the Human Medial Temporal Lobe," *Journal of Neuroscience*, 26 (40), 10232–10234.
- Wehr, Michael and Gilles Laurent (1996), "Odour Encoding by Temporal Sequences of Firing in Oscillating Neural Assemblies," *Nature*, 384 (6605), 162–66.
- Witte, Kim (1992), "Putting the Fear Back into Fear Appeals: The Extended Parallel Process Model," *Communications Monographs*, 59 (4), 329–49.
- Wixted, John T. (2007), "Dual-Process Theory and Signal-Detection Theory of Recognition Memory," *Psychological Review*, 114 (1), 152–76.
- Wolburg, Joyce M. (2006), "College Students' Responses to Anti-Smoking Messages: Denial, Defiance, and Other Boomerang Effects," *Journal of Consumer Affairs*, 40 (2), 293–323.

Copyright of Journal of Marketing Research (JMR) is the property of American Marketing Association and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.