Human single-neuron responses at the threshold of conscious recognition

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We studied the responses of single neurons in the human medial temporal lobe while subjects viewed familiar faces, animals, and landmarks. By progressively shortening the duration of stimulus presentation, coupled with backward masking, we show two striking properties of these neurons. (*i*) Their responses are not statistically different for the 33-ms, 66-ms, and 132-ms stimulus durations, and only for the 264-ms presentations there is a significantly higher firing. (*ii*) These responses follow conscious perception, as indicated by the subjects' recognition report. Remarkably, when recognized, a single snapshot as brief as 33 ms was sufficient to trigger strong single-unit responses far outlasting stimulus presentation. These results suggest that neurons in the medial temporal lobe can reflect conscious recognition by "all-or-none" responses.

consciousness | memory | visual perception | medial temporal lobe | epilepsy

Our brain has the remarkable ability of creating coherent percepts despite constant changes in the visual environment. For example, our perception of a face is similar whether we see it for a fraction of a second or for much longer periods of time. Critically, below a certain temporal threshold, recognition appears to fail in an "all-or-none" fashion. Previous studies have addressed this question by using functional magnetic resonance imaging (fMRI) in humans (1). However, how our visual system represents this temporal nonlinearity at the single-neuron level is still an open question, because the fMRI signal gives only an indirect and temporally sluggish measure of the activity of large neural populations.

Visual perception is processed along the ventral visual pathway, going from neurons in early visual areas extracting local visual features, to neurons in higher areas involved in the encoding and recognition of the actual object that is being seen (2–6). This processing culminates in the medial temporal lobe (MTL), which receives massive inputs from high-level visual areas. Converging evidence has shown that the MTL is not part of the recognition process *per se* (but see ref. 7), and it rather mediates the transformation of percepts into memories (8, 9). However, given their function in long-term memory storage, MTL neurons can indirectly "signal" perception processes because percepts should be represented in MTL if they are going to be stored in long-term memory for later recall. In particular, we recently reported the presence of neurons in the human MTL that fired selectively to different views of specific individuals, and in some cases even to their written name (10), thus showing the existence of an abstract representation that is invariant to basic visual features.

To study the relationship of these MTL neurons to stimulus duration and how this correlates to conscious recognition, in the current study, we used different durations of stimulus presentations immediately followed by a mask. Stimulus durations were chosen to be at the threshold of recognition, so that the same visual stimulus could be recognized in some trials and not in others. By using this simple experimental manipulation we then asked (*i*) whether, and how, the activity of these neurons changed with stimulus duration and (*ii*) whether this activity depended on the subjects' recognition. Our results show highly nonlinear, all-or-none responses associated with the subjects' recognition state. These responses were clearly dissociated from the physical stimulus presentation durations because they far outlasted the short presentation times.

Results

In 13 experimental sessions with five patients, we recorded from a total of 440 MTL units (161 single units and 279 multiunits; see *Materials and Methods*). The distribution of these cells was as follows: 44% were located in hippocampus, 29% in entorhinal cortex, 19% in amygdala, and 8% in the parahippocampal gyrus. Of the 440 MTL units, 68 (15.4%) elicited a significant response to a total of 98 pictures. Of the 98 pictures eliciting responses, 71 corresponded to faces, 19 to landmark buildings, and 8 to animals. There were no clear differences for the different MTL areas. Most of the responsive units were located in hippocampus (36/68, 53%), but this was mainly due to the larger sampling in this area (see above). Of the remaining responsive cells, 27 (40%) were located in the entorhinal cortex, 4 (6%) in amygdala, and 1 (1%) in the parahippocampal gyrus.

Behavioral Responses. Supporting information (SI) Fig. 7 shows the relative number of times the pictures were recognized for the different presentation durations. In agreement with previous studies (1, 11, 12), there is an increasing number of "recognized" trials with increasing presentation durations. For all stimulus durations, the percentage of trials in which pictures were recognized was relatively high, going from 47% for 33 ms to 96% for 264 ms. Considering the 33-ms presentations, for 16 of 98 stimuli the patients could not recognize the picture shown in any of the trials, and in 63 of 98 cases the patients reported not recognizing the picture in at least half of the trials. Although we used the same mask for all pictures, this finding shows that the mask was effective in blocking retinal persistence of the images. The fact that patients could still, in some cases, recognize pictures shown for only 33 ms and that such short presentations elicited responses (see Figs. 1 and 3) is in agreement with previous reports in monkeys (11–14) and can be attributed to the use of visual cues and perceptual priming, which increases recognition for briefly presented images (15). In human fMRI studies (1), the performance was reported to be lower compared

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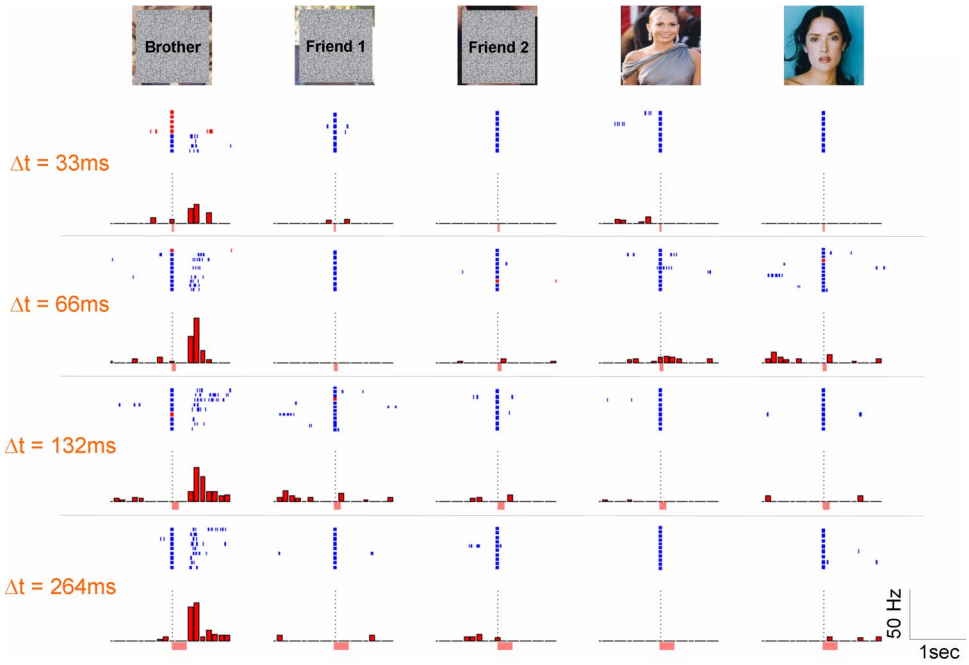

Fig. 1. Raster plots and peristimulus time histograms (PSTH) (100-ms bin size) of a single neuron in the right hippocampus that responded selectively to a picture of the patient's brother. Pictures are covered for privacy. The different presentation durations are shown with the light red bars at the bottom of the PSTH plots. Trials where the pictures were (were not) recognized are displayed in blue (red). Note that responses changed dramatically depending on whether the picture was recognized or not and far outlasted the stimulus presentation duration.

to our study for short presentation times. This difference can be attributable to stronger priming a effect in our study because the patients were repeatedly exposed to a rather small set of pictures.

To test the hypothesis of perceptual priming, we analyzed whether the percentage of recognized trials depended on the presentation order in the stimulus sequence. As shown in SI Fig. 8, there is a clear increase in the number of correct responses with trial number for the 66-ms and 132-ms presentations (ANOVA, $P < 10^{-6}$, and $P < 10^{-5}$, respectively). For the 33-ms presentations, there were no significant differences with trial number because the pictures were usually hard to recognize even after many presentations. For the 264-ms presentations, the pictures were easily recognized already from the first trial and therefore there were also no significant changes with trial number.

Fig. 2. Raster plots and PSTH of a single neuron in the right entorhinal cortex that fired selectively to pictures of the World Trade Center. Note the striking difference in the responses to presentations when the picture was recognized (in blue) and when it was not (in red).

Single-Cell Responses. SI Fig. 1 shows a single neuron in the right hippocampus that responded selectively to a picture of the patient's brother (picture covered for privacy). Because of space limitations, in this and the next figures, the responses of only five pictures will be shown. Responses to all of the pictures are presented in SI Figs. 9–12. In no case there was a significant response to the pictures not shown. Trials in which the pictures were recognized are indicated by blue markers, and those in which they were not recognized are indicated by red markers. In agreement with previous findings (10), this neuron was highly selective, and it did not respond to pictures of two close friends of the patient or to other famous people. For all presentation times, the response started at ≈300 ms after stimulus onset, which was relatively long after the picture was no longer in view. This is the same latency we previously reported when studying invariance of MTL responses with pictures shown for 1 s (10). Interestingly, there was a striking difference in the firing of the neuron when the picture was recognized compared with when it was not. This was clearly evident in the 33-ms presentations, where in only about half of the presentations the images were recognized. The neuron fired in an all-or-none fashion, going from a nearly silent baseline to close to 50 Hz for recognized trials, and it did not fire at all for nearly all nonrecognized trials. Note also that when the picture was recognized, responses were largely similar for all stimulus durations. Importantly, the duration of the response far exceeded the duration of the image presentations.

Fig. 2 shows a single unit in the right entorhinal cortex of another subject that fired selectively to pictures of the World Trade Center. From a nearly silent baseline activity, the neuron responded with up to 10 spikes per s. As with the previous example, the response of this neuron to all other stimuli was not significant. The patient reported not recognizing the picture of the World Trade Center in all trials with 33-ms duration and in eight trials with other durations (in red). Note that, corresponding with the behavioral report, there was no observable response during trials where the picture was not recognized. The difference between recognized and nonrecognized trials was remarkable for the 66-ms presentations, where again it is clear that the neuron fired in an all-or-none fashion. In fact, for the three trials in which the picture was recognized, the neuron fired 5–8 spikes between 300 ms and 1,000 ms after stimulus onset, and for the five trials in which the picture was not recognized, the neuron did not fire a single spike.

Fig. 3 shows a single neuron in the right hippocampus of another patient that responded selectively to a picture of the actress Whoopi Goldberg. This neuron had a response going up to 50 Hz from an average baseline firing rate of 0.05 Hz; i.e., a 1,000-fold increase in firing rate. In the case of picture presentations of Whoopi Goldberg, the patient reported to recognize her in all trials, and corresponding to that report the neuron responded with a similar firing rate at all presentation durations. The fact that the patient could recognize the picture of Whoopi Goldberg even with 33-ms presentations can be attributed to the use of basic cues such as the overall yellow tone and the pose compared to the other pictures.

Fig. 4 shows a single neuron in the left hippocampus that fired to a picture of Elvis Presley and a picture of ex-president Ronald Reagan. Again, and particularly for the presentations of pictures of Elvis Presley, there was a remarkable correlation with behavior. In fact, there was not even 1 spike fired in any of the five trials where the picture was not recognized.

Population Responses. Given the previous single-cell examples showing a remarkable correlation to behavior, it is important to examine how consistent the relationship to recognition was across the entire population of responsive neurons. For this, we pooled together all responsive units. To control for the fact that different neurons have different spike counts, we normalized the firing to each picture eliciting responses by the maximum median firing (across trials) in the 300- to 1,000-ms window (i.e., the maximum over the four presentation times). Fig. 5 displays the normalized responses of all the responsive neurons at all stimulus presentations, separated into recognized and nonrecognized trials. The difference between recognized and nonrecognized states is quite striking, both in signal amplitude and in response reliability. Furthermore, Fig. 5 clearly reveals the dissociation between stimulus presentation duration and the neuronal responses, i.e., the fact that the response lasted for a far longer duration than the stimulus exposure times.

Using the normalized firing between 300 ms and 1,000 ms after stimulus onset, we statistically compared these responses with a two-way ANOVA (factors were stimulus duration and response type; see *Materials and Methods*). There were statistically significant effects both of stimulus duration ($P < 10^{-4}$) and response type ($P < 0.005$). The interaction between both factors was not significant ($P = 0.6$). Interestingly, post hoc analysis showed that the significant difference with stimulus duration was given by a larger firing for the 264-ms presentations compared to the other three durations for the recognized trials ($P < 10^{-4}$ in all cases).

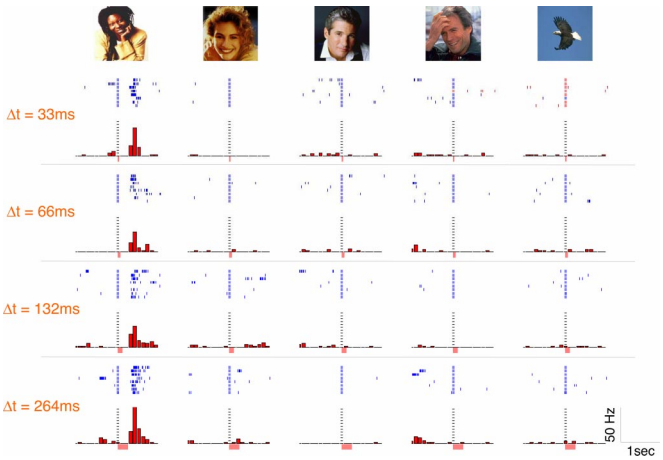

Fig. 3. Raster plots and PSTH of a single neuron in the right hippocampus that responded selectively to pictures of the actress Whoopi Goldberg. In this case the patient reported to recognize all picture presentations of Whoopi Goldberg (in blue), even for the 33-ms presentations.

Fig. 4. Raster plots and PSTH of a single unit in the left hippocampus that responded to a picture of Elvis Presley and a picture of Ronald Reagan. Note again the lack of responses in the nonrecognized trials.

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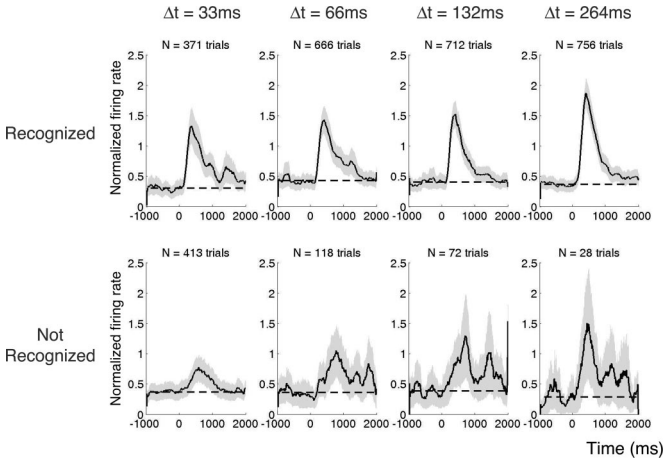

Fig. 5. Normalized average responses of all neurons for the different presentation durations, separated into recognized and nonrecognized trials. The horizontal dashed lines mark the mean baseline activity, and the bands show the SEM. Three effects can be seen. (*i*) a striking difference in amplitude and variability between recognized and nonrecognized conditions. (*ii*) A far longer neuronal response than stimulus presentation duration. (*iii*) A largely ''unitary'' response shape with only marginal changes with stimulus durations.

There were no significant differences among the 33-ms, 66-ms, and 132-ms durations.

Of particular importance is to analyze those cases where the same picture durations elicited both recognized and nonrecognized trials, because these cases eliminate the possibility that the difference in responses was caused by different stimulus exposure durations. In particular, we studied in more detail 29 responses for which we had equal number of recognized and nonrecognized trials (four each) for a given duration. Fig. 6 shows the average firing for the recognized and nonrecognized trials. As in the previous case, responses were normalized to account for the fact that different neurons may have different firing. We observe that the response for the recognized trials is larger than for the nonrecognized ones. This difference was highly significant (T test, $P < 10^{-6}$; see *Materials and Methods*) and clearly argues against a possible confound of the effects of recognition with stimulus duration.

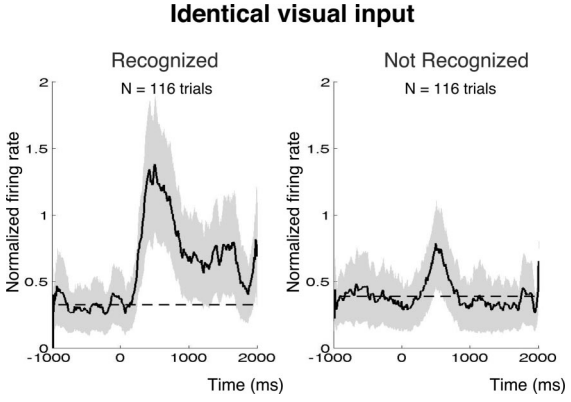

Fig. 6. Normalized average responses of the cases in which the same duration elicited equal number of recognized and nonrecognized trials. The horizontal dashed lines mark the mean baseline activity and the bands show the SEM. Note that for the same stimulus and the same duration, i.e., exactly the same visual inputs, there was a significantly higher response for the trials in which the pictures were recognized, according to the subjects' reports (T test, $P < 10^{-6}$).

Single-Trial Prediction of the Subjects' Responses. Based on the firing of individual responsive neurons, can we tell whether the picture eliciting responses was recognized or not? We used a Receiver Operator Characteristic (ROC) analysis to determine whether an ideal observer could use the firing in each trial to make these predictions (see *Materials and Methods*). For this, we considered those responses where in at least five trials the picture was not recognized (55 of 98 responses). If, as described above, recognized trials elicit a larger firing than the nonrecognized ones, the ROC curves will have an area close to 1. Conversely, if there is no difference in the firing to recognized and nonrecognized trials, then hits and false positives will be equally likely and the ROC curves will have an area close to 0.5 (see *Materials and Methods*).

SI Fig. 13 shows the distribution of ROC areas for all of the 55 responses with at least 5 nonrecognized trials. The median of this distribution was 0.71. To evaluate statistical significance, we repeated the same ROC analysis but using the baseline period between 1,000 ms and 300 ms before stimulus onset. In this case, the median of the distribution was 0.52. The distribution of ROC areas using the number of spikes between 300 ms and 1,000 ms after stimulus onset was significantly larger than the one obtained with the baseline period ($P < 10^{-4}$; see *Materials and Methods*).

Discussion

In the current study, we examined differential responses of MTL neurons to recognized and nonrecognized pictures by using short presentation durations together with backward masking. Moreover, the effect of stimulus duration on the firing amplitude of these cells and their responses to very short presentations was assessed. The main finding is that the firing of MTL neurons showed a significant relationship with the subjects' conscious perception. Furthermore, the neuronal firing was not a direct reflection of the stimulus duration, showing a much longer response that changed only marginally with stimulus duration. This ''memory-like'' effect cannot be explained by a sustained activity at low level visual areas because these should have likely been erased by the ensuing mask. It is indeed remarkable that a picture flashed for only 33 ms elicited a cascade of neural processes that culminated in very selective MTL responses ≈300 ms after stimulus onset, continued long after the picture was removed from view, and lasted for far longer durations.

Pooling together all of the responses, we found a significant effect both of stimulus duration and recognition. It is important to note that the difference in firing with stimulus duration was attributable to a stronger firing for the 264-ms presentations, because the 33-ms, 66-ms, and 132-ms presentations did not show significantly different response amplitudes. This finding argues against the possibility that the increased activity associated with recognition was simply caused by a better performance at increased stimulus durations. In fact, at the the main ''recognition effect'' was evident at the transition from 33 to 64 ms, whereas the main ''duration effect'' was evident transition from 132 to 264 ms. We cannot assert with the current experiment why the firing for the 264-ms presentation was significantly larger, but in principle it could be reflecting a sustained response driven by the long presentation of the stimulus, even after recognition is achieved.

By considering those cases in which we had both recognized and nonrecognized trials for a given duration, it was possible to dissociate the effect of recognition from the one of stimulus duration. We found that responses to recognized trials were significantly higher than the ones to the nonrecognized ones, which means that exactly the same visual inputs elicited different responses in the neurons according to the subjects' perception. Furthermore, the firing of these cells allowed the prediction in

each trial of whether a picture was recognized or not far above chance.

As expected, the recognition performance of the subjects increased monotonically with stimulus duration, but in a highly nonlinear manner. We also showed an effect of perceptual priming, because for the 66-ms and 132-ms presentations the recognition rate increased significantly with trial number. This finding demonstrates the possible use of basic visual cues that help to identify the picture when briefly shown and trigger nearly the same response as when the picture is shown for relatively large durations. For the 33-ms and 264-ms presentations, the priming effect was not significant because the pictures were hardly recognized in any of the trials in the first case and were already recognized from the first trial in the latter one. Compared with our behavioral responses, previous studies (1) reported lower performances for short presentation times. This difference can be attributed to the fact that Grill-Spector and colleagues (1) used a much larger set of pictures, thus diminishing the effect of perceptual priming we found in our data. In fact, by using a database of 448 images, these authors found gradual improvements in the recognition rate over a period of days, whereas in our case, with 16 images, the improvements in recognition were already visible after a few trials.

One of the main factors that may have contributed to the variability of the subjects responses is the degree of attention they pay to the stimuli in each trial. Modulations of single-cell responses attributable to attention have been well documented in monkeys (16, 17). However, it should be noted that attention did not necessarily affect the firing of MTL neurons directly, because it could have also modulated the responses of neurons in earlier visual areas, thus precluding the propagation of information (in nonrecognized trials) before reaching MTL. In any case, regardless of whether these attention effects may have been resolved in earlier visual areas, it is interesting that MTL neurons reflect the differences between recognized and nonrecognized visual stimuli in such a highly nonlinear fashion.

An alternative explanation for the variability in the responses is that the subjects did not look at the pictures in the nonrecognized trials. However, this is very unlikely given the priming effect we found in our data (i.e., nonrecognized trials tend to be the first ones in the sequence) and the increase in recognition rate with duration, in agreement with previous reports (1, 11–14). Furthermore, such a failure to look at the stimuli should have been equally detrimental at the 33- and 66-ms durations, which are both too fast to allow corrective refixation. Our results show that in fact the biggest increase in recognition performance and neuronal responses occurred precisely at the transition from 33 ms to 66 ms, strongly arguing against this possible confound.

Our finding of significant differences in the cell's firing to recognized and nonrecognized trials, by using fast stimulus presentations, complements and reinforces previous reports of single-cell correlates of visual perception using binocular rivalry in earlier visual areas in monkeys (5, 18), motion detection in monkey MT (19, 20), and flash suppression in humans (21). Note that our yes/no measure of recognition was particularly subjective, and it may have included mistakes in correct identification. For example, the patient may have reported recognizing the picture of a certain person but thinking it was another one. Despite this possible confound, the neuronal correlation to behavior was remarkable. These results are compatible with the fMRI studies of Grill-Spector and colleagues (1), which showed highly nonlinear activations related to recognition in high-order human object areas, the lateral occipital complex and the fusiform face area (FFA). They are also in agreement with reports of FFA activations for detected compared to nondetected faces (22) and with more recent findings showing correlation with behavior (recognized or not) in the lateral occipital complex (23).

It should be noted that, as for place cells in the rodent hippocampus (24), MTL neurons have very sparse responses and they lack topographical organization; i.e., close-by neurons fire to different stimuli (10, 25). For this reason, it is unlikely that the neural responses we describe here for MTL cells could be observed with imaging techniques such as fMRI (26).

It also is interesting to compare our results to previous studies in monkey inferior temporal cortex (IT) and superior temporal sulcus (STS) (11–14), which also reported response durations far exceeding the stimulus duration. In particular, by using gaps between consecutive stimuli, it has been shown that neurons in the STS of monkeys continue processing a stimulus as if it was still present on the screen (27). This effect is interesting because it may point to a short-term storage or reverberatory dynamics in high-order visual cortex. Such long-lasting responses were also reported in the human visual cortex by using fMRI (28). Furthermore, the monkey studies reported clear differences for the different presentation durations, which were interpreted as evidence for a role of these neurons in visual perception. It should be noted that monkeys are usually overtrained in these tasks, a fact that may affect the interpretation of the results because they could be attributed to perceptual or training effects (see, for example, ref. 29). Our study of MTL regions shows strong single-cell responses signaling perception in naïve human subjects, and it therefore helps to validate related findings in the animal literature. There is, however, a major difference between our findings and those reported in high-level visual areas of monkeys. In our case, given the relatively long latency of the responses compared to the latencies reported for picture recognition (30), it is highly likely that the MTL neurons reported here are not part of the recognition process *per se*. This finding is in agreement with lesion studies and substantial evidence from patient H.M. and others (8, 9). The fact that MTL cells seem to be mainly modulated by the conscious perception of the images is in line with our previous suggestion that these cells may be underlying the link between consciously perceived inputs and long-term memory (10, 31).

Materials and Methods

Subjects and Recordings. The data were collected from 13 sessions in five patients with pharmacologically intractable epilepsy (all right-handed, two males, three females, 19 to 39 years old). Extensive noninvasive monitoring did not yield concordant data corresponding to a single resectable epileptogenic focus. Therefore, they were implanted with chronic depth electrodes for 7–10 days to determine the seizure focus for possible surgical resection (32). After implantation, the anticonvulsive medication was progressively lowered to increase the occurrence of seizures for clinical evaluation. Because results were consistent across subjects, who had different medications and doses according to their clinical cases, it is very unlikely that a specific medication could have affected the present results. Here, we report data from sites in the hippocampus, amygdala, entorhinal cortex, and parahippocampal gyrus. All studies conformed to the guidelines of the Medical Institutional Review Board at University of California at Los Angeles. The electrode locations were based exclusively on clinical criteria and were verified by MRI or by computer tomography coregistered to preoperative MRI. Each electrode probe had a total of nine microwires at its end, eight active recording channels and one reference. The differential signal from the microwires was amplified by using a 64-channel Neuralynx system, filtered between 1 and 9,000 Hz and sampled at 28 kHz.

Subjects sat in bed, facing a laptop computer with a 60-Hz refreshing rate monitor, on which 16 pictures of individuals, animals, landmarks, or objects were shown at four different durations: 33 ms, 66 ms, 132 ms, and 264 ms (2, 4, 8, and 16 refresh screens, respectively). The pictures used were selected based on screening sessions, in which a relatively large set of images (83 to 99) of persons, landmarks and animals were shown for 1 s to the patient, six times each in pseudo-random order (for details, see ref. 10). The data were quickly analyzed offline to determine the stimuli that elicited responses in at least one unit. From the screening sessions, the 16 pictures eliciting the largest responses in any neuron were further tested at all four durations. In one of the sessions, only seven pictures were used. Before the experiments, the subjects confirmed they recognized the pictures of persons, landmarks, or animals

used. Picture presentations were immediately followed by a mask lasting 467 ms, 434 ms, 368 ms, and 236 ms, respectively (i.e., the duration of each picture presentation with mask was 500 ms). The mask was used to block retinal persistence of the images and it was generated with randomly shuffled pieces taken from different images. It was the same for all pictures to avoid giving extra information about the picture shown (i.e., that the patient could associate a picture with its corresponding mask, because of the relatively low number of pictures we used). For each duration, the pictures were shown eight times in pseudo-random order. The images were displayed at the center of the screen and covered $\approx$1.5° of visual angle. Subjects were instructed to pay attention to the picture presentations and to respond whether they recognized the specific person, animal, or landmark shown in the pictures (e.g., Julia Roberts, an eagle, Tower of Pisa) by pressing the left and right arrow keys, respectively. Subjects did not report what they saw. It should be noted that in our clinical setup the total time of the experiments was limited to about half an hour per recording session, which constrained the total number of pictures that could be presented (only 16), thus increasing the possibility of perceptual priming, i.e., learning the identity of the pictures from visual cues. For this reason, it was not always possible to have sufficient nonrecognized trials for presentations of the pictures eliciting responses.

Data Analysis. Spike detection and sorting was applied to the continuous recordings by using a recently proposed clustering algorithm (33). After sorting, the clusters were classified into single units or multiunits based on: (*i*) the spike shape and its variance; (*ii*) the ratio between the spike peak value and the noise level; (*iii*) the ISI distribution of each cluster; and (*iv*) the presence of a refractory period for the single units, i.e., $<$1% spikes within $<$3-ms ISI. Because, as we recently showed, the firing of MTL neurons starts 300 ms after stimulation (10), the response to a picture at a specific duration was defined as the median number of spikes across trials between 300 and 1,000 ms after stimulus onset. The baseline for each picture was the median number of spikes between 1,000 and 300 ms before stimulus onset. A unit was considered responsive if the activity to at least one picture fulfilled two criteria: (*i*) the median number of spikes was larger than the average baseline (for all pictures) plus 5 SD and (*ii*) the median number of spikes was at least 2 (10). A picture was considered as eliciting a response in a given neuron if for at least one of the four presentation times there was a significant response.

Statistical Analysis. First, to evaluate the effects of stimulus duration and recognition across the entire population of neurons, we pooled together all significant responses. To take into account the fact that different neurons have different spike counts, we normalized the responses of each neuron by the maximum median firing (across trials) in the 300- to 1,000-ms window (i.e., the maximum over the four presentation times). A two-way ANOVA with factor stimulus duration (33 ms, 66 ms, 132 ms, and 264 ms) and response type (recognized or not) was performed. Entries to the ANOVA test were the number of spikes between 300 and 1,000 ms for each trial.

Second, to dissociate the effect of recognition from stimulus duration, we considered only those cases where for the same stimulus duration we had enough recognized and nonrecognized trials. For this, we pooled together, after normalization, those responses with four recognized and four nonrecognized trials at a given duration and compared the firing in both conditions with a *T* test.

ROC Analysis. We evaluated how well an ideal observer could use the firing of individual responsive neurons to predict whether the picture eliciting responses was recognized or not in each trial by using a ROC analysis (34). For this, we considered pictures eliciting responses with at least five nonrecognized trials, which was the case for 55 of 98 responses. Entries to the ROC analysis were the total number of spikes in each trial between 300 ms and 1,000 ms after stimulus onset. The hit rate (*y* axis) was defined as the relative number of recognized trials with a response larger than a sliding threshold. Similarly, the false positive rate (*x* axis) was defined as the relative number of nonrecognized trials with a response larger than the sliding threshold. Note that in our dataset we did not have behavioral false positives (i.e., catch trials in which the subject may falsely report recognizing a picture) and, therefore, the ROC analysis was based on behavioral hit rates. ROC curves were obtained by gradually lowering the threshold. Starting with a very high threshold (no hits, no false positives), if there is a larger firing of the neuron for recognized trials, the ROC curve will show a steep increase when lowering the threshold. If the neuron responds equally to recognized and nonrecognized trials, it will have a similar relative number of hits and false positives, and the ROC curve will fall along the diagonal. In the first case, the area under the ROC curve will be close to 1, whereas in the latter case it will be $\approx$0.5. To estimate statistical significance, these ROC areas were compared with those obtained by using the total number of spikes during baseline (between 300 ms and 1,000 ms before stimulus onset) with a *T* test.

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