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COMPARATIVE STUDY ON THE OFFSET RESPONSES OF SIMPLE CELLS AND COMPLEX CELLS IN THE PRIMARY VISUAL CORTEX OF THE CAT

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Abstract—Simple and complex cells are two basic and distinct functional types of neurons in the mammalian primary visual cortex. Here, we studied the onset response and the offset response of simple and complex cells to a flashing visual stimulus in the cat's area 17. Compared with simple cells, complex cells exhibited greater similarity between the onset and offset responses in peak latency. For simple cells, onset response had greater peak amplitude and signal-to-noise ratio than offset response, and for complex cells, vice versa. For both types of cortical cells, the amplitude of offset responses increased with stimulus duration within 100 ms significantly, while the onset response did not. However, to elicit a detectable offset response, complex cells tended to require shorter stimulus duration than simple cells did. In regard to the similarity of psychophysical data, these results suggest that the rebound offset response of cortical cells to disappearance of a visual pattern might be correlated to visual persistence in humans.

Key words: off-response, area 17, visual cortex, latency, simple cell, complex cell.

Since Hubel and Wiesel's pioneering work (Hubel and Wiesel, 1962, 1968), simple and complex cells have been found in the primary visual cortex of many mammalian species. Besides the most well studied monkeys and cats, other species like tree shrews (Kaufman and Somjen, 1979), rats (Girman et al., 1999), mice (Drager, 1975), rabbits (Glanzman, 1983) and marsupials (Ibbotson et al., 2005) have also been studied. Furthermore, cells with simple and complex-like behavior have also been reported in other sensory cortices, such as the primary auditory cortex of the ferret (Kowalski et al., 1996) and the primary somatosensory cortex of primates (DiCarlo and Johnson, 2000). It turns out that simple and complex cells play important roles in signal processing in the sensory system of mammals. Thus, it is fundamental to understand them better in order to know more about how the brain works.

It is known that simple cells have separated but adjacent 'on'(bright) and 'off'(dark) subregions in their receptive fields (RFs) (Hubel and Wiesel, 1962, 1968), and respond linearly to light intensity modulation in their RFs (Movshon et al., 1978a); whereas the complex cells have overlap 'on–off' RF subregions and respond nonlinearly (Hubel and Wiesel, 1962, 1968; Movshon et al., 1978b). Hubel and Wiesel (1962, 1968) have proposed a hierarchical model of how simple and complex cells form their RFs. This model consists of two stages: at the first stage, the aligned convergence of the 'center-sound' lateral geniculate nucleus (LGN) input constructs the orientated simple cell RF, which has distinct 'on' and 'off' subregions; at the second stage, convergence of simple cell input constructs the complex cell RF which is 'on–off' overlapped. This model is simple and straightforward, and has gained considerable supporting evidence at both stages (Chapman et al., 1991; Reid and Alonso, 1995; Ferster et al., 1996; Alonso and Martinez, 1998; Chung and Ferster, 1998; Martinez and Alonso, 2001). However, debates remain about this model both at the first stage (Gillespie et al., 2001; Shapley et al., 2003) and the second stage (Mel et al., 1998), so different models have been proposed (Stone et al., 1979; Chance et al., 1999; Mechler and Ringach, 2002; Tao et al., 2004).

For half a century, most electrophysiological studies about simple and complex cells have focused on their onset responses. Although it is well known that a bright bar in a simple cell's 'off' discharge field, or a dark bar in its 'on' discharge field, can elicit offset responses, few studies have focused on the offset response aspects and the corresponding difference between simple cells and complex cells, which could help to gain new insight into the formation of this dichotomy of neural cell types. In the current study, a comparison was made between the properties of the offset and onset response to a stationary flashing grating between simple and complex cells in the primary visual cortex of the cat.

EXPERIMENTAL PROCEDURES

Surgical procedures and electrophysiological recording

Visual responses were extracellularly recorded from primary visual cortex in the anesthetized, paralyzed adult cats. The detailed methods used in this study for surgical procedures and electro-

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Abbreviations: IOP, intraocular pressure; LGN, lateral geniculate nucleus; RF, receptive field.

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physiological single unit recording have been described elsewhere (Shou and Zhou, 1989; Zhou et al., 1994; Chen et al., 2005). All procedures conformed to the guidelines of the Chinese Association for Physiological Sciences on the Ethical Use of Animals and the National Institutes of Health for Care and Use of Laboratory Animals (revised 1996). All experiments were designed to minimize the number of animals used and suffering. Cats were initially anesthetized with ketamine (25 mg/kg; Hengruei Pharmaceutical Inc., Shanghai, China). During the rest of the experiment, light anesthesia was maintained with i.v. sodium pentobarbital (Shanghai Chemical Reagent Co., Shanghai, China) given at an initial dose of 4 mg/kg followed by an infusion of 3 mg/kg●h. All pressure points and incisions were infiltrated with a long-acting anesthetic (1% lidocaine HCl; Shanghai Chemical Reagent Co.). Gallamine triethiodide (Flaxedil; Shanghai Chemical Reagent Company; 10 mg/kg●h) was used for immobilization. The animal was artificially ventilated with room air after tracheal cannulation was performed; end-tidal CO_2 was kept between 3.5 and 4.0% by adjusting the respirator. Body temperature was maintained near 38 °C with a heating pad automatically. Electroencephalogram (EEG) and electrocardiogram (ECG) were continuously monitored for estimating the depth of anesthesia. The pupils were dilated with atropine (0.5%; Harvest Pharmaceutical Inc., Shanghai, China) and the nictitating membrane was retracted with Neosynephrine (2%; Shanghai Chemical Reagent Co.). The eyes were carefully refracted and corrected with contact lenses of appropriate refractive power. To reduce the amount of spherical aberration, artificial pupils (3 mm in diameter) were placed in the front of each eye.

The optic nerve head, retinal vessels and the area centralis of the eye were mapped on a sheet of paper covering the screen of the visual stimulator using the fundus reflective projection method (Fernald and Chase, 1971). This was done repeatedly throughout the experiment to ensure that the effect of eye movement was prevented completely. The primary visual cortex at Horsley-Clarke coordinates P 1–8 and L 0–3 was exposed for electrophysiological recording. The action potentials of the cells in visual cortex in the cat were recorded with a glass micropipette filled with 3 M NaCl, whose impedance ranged from 5 to 15 MΩ. The glass microelectrode was positioned perpendicularly to the surface of the exposed cortex covered with agar. Action potentials of the recorded neuron were amplified then fed to an audio monitor and a data acquisition system (CED micro 1401, Cambridge Electronic Design, UK). The raw data sampled at 2 kHz were stored in a computer for analyzed (Spike2, version4; Cambridge Electronic Design).

Visual stimuli

Visual stimulation was generated on a computer display (FlexScan F931; EIZO, Japan) using a Visual Stimuli Generator 5 (Cambridge Research Systems Ltd., UK), which trigged the computer to collect neurons firing in a precisely time-locked way. The stimulus patterns were stationary sinusoidal gratings mainly, or drifting gratings in case of need with a uniform background. The mean luminance of either the grating or the background was identical (17 cd/m^2). The contrast of the gratings was 70%.

The RFs of isolated units were first mapped by using a hand-held target on a tangent screen 57 cm from the cat's eye. For most of the cortical cells recorded, after the center of the RF was carefully determined, a drifting grating (temporal frequency 2 Hz) was centered precisely on the center of the cell's RF. Then, a grating diameter-response amplitude curve was measured when the diameter of the grating area was gradually increased. Accordingly, a round grating area of the optimal diameter (decided from the peak of the diameter-response amplitude curve) was used to elicit neurons' responses, and then to measure the orientation tuning curve and spatial frequency tuning curve for each cell.

After these routine measurements, flash stationary gratings were briefly presented on a round area of the optimal diameter in each cell's optimal spatial frequency and orientation. The whole sequence of stimuli contained 50–100 grating patterns interleaved by a mean luminance blank, during which a cell's spontaneous activity was recorded. Thus, each grating pattern was presented in a stimulus duration, which was defined as the stimulus on period, a blank of mean luminance was presented on the screen in an off duration, which was defined as the stimulus off period prior to the next grating.

Data analysis

Cortical neurons were categorized as simple cells or complex cells on the basis of the segregation (simple cells) or overlap (complex cells) of 'on' and 'off' subfields (Hubel and Wiesel, 1968; Schiller et al., 1976), as well as the relative modulation (ratio of the first harmonic amplitude to the mean response, F1/F0) of the cells' response to gratings of the optimal spatial frequency. Simple cells usually appeared to have relative modulation values in excess of 1.0, while complex cells' values were less than 1.0 (Movshon et al., 1978a,b; Skottun et al., 1991).

The mean spontaneous activity plus two times its standard deviation (2 S.D.) was used to determine a cell's responding threshold. Only the cells, whose maximum response evoked by either the onset or offset of a grating were greater than the threshold, were included in the further analysis in this study. The peak latency was defined from the onset or the offset of stimulus to its corresponding response peak.

Calculation of cumulative detectability

Detectability was initially defined as a neuron's capacity to distinguish a stimulus by Müller et al. (2001). Similarly, we used the equation:

$$d' = \frac{\mu_1 - \mu_2}{\sqrt{(\sigma_1^2 + \sigma_2^2)/2}}$$

to calculate the detectability d' where μ_1 was the mean firing rate of a neuron responding to a given stimulus and σ_1 was the standard deviation of trials; μ_2 and σ_2 were the mean and standard deviation of spontaneous activity, respectively. Given two alternatives, when the value of detectability $d'=0$, an ideal observer will detect the stimulus correctly on 50% of trials; when $d'=1$, the detection will be 76% correct; when $d'=2$, it will be 92% correct. In this study, there were two separate calculations of the cumulative detectability within a given integrated time window for the stimulus on period (from the grating onset to the offset) and for the stimulus off period (from the grating offset to next grating onset). The integrated time window for calculating cumulative detectability was increasing in a 20 ms step, i.e. from the onset (or offset) to 20 ms, then from the onset to 40 ms, 60 ms . . ., and so on.

RESULTS

Phase dependence and latency

Single neuron activity was recorded from the primary visual cortex of the cat. The RF centers of all cells studied were located within 10 deg from the area centralis of the retina. Among 88 recorded neurons, 55 (62.5%, 31 simple and 24 complex cells) responded transiently to the disappearance of the flash grating stimuli following a response to the stimulus onset (hereafter, referred as the offset response and the onset response, respectively). Due to the separate 'on' and 'off' subregions in the RF, the onset

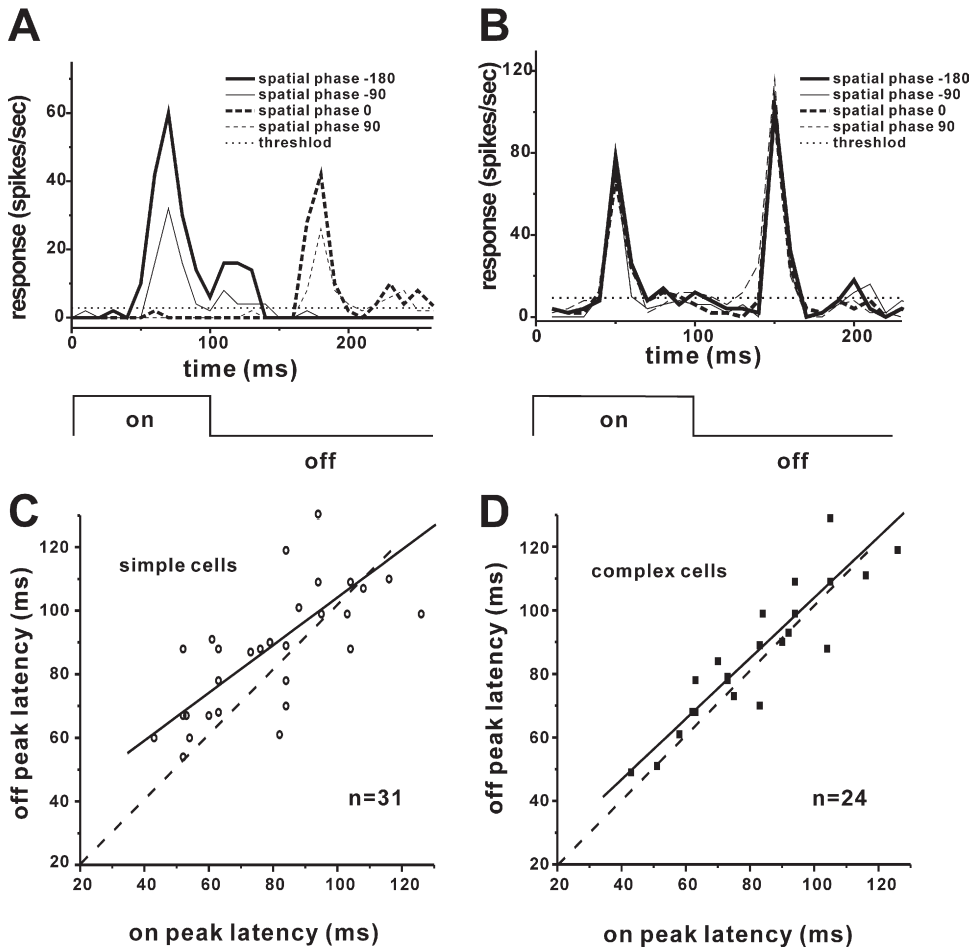

Fig. 1. Difference in response to a flashing stationary grating followed by a blank between simple and complex cells of area 17 in the cat. (A, B) PSTHs of responses to grating stimuli in the cell's preferred orientation at different spatial phases for a simple cell (A) and a complex cell (B). Lines below the PSTHs indicate the on and off period of the grating. Curves of different lines represent responses elicited by different spatial phases of gratings: thick solid, −180°; thin solid, −90°; thick dash, 0°; thin dash, 90°. Dotted lines show the threshold (spontaneous activity+2 S.D.). Bin width was 10 ms. Note that the simple cell shows spatial phase dependent, but the complex cell does not. (C) Comparison of the offset response peak latency and the onset response peak latency for 31 simple cells studied. The two sets of latency data scattered around the diagonal line of slope 1 were significantly correlated ($r=0.76$; $P<0.0001$). The solid line was the linear fit of the data ($y=0.75x+29.1$) and significantly differed from 1 (*t*-test, $P=0.048$), and the intercept was significantly different from 0 (*t*-test, $P=0.0081$) as well. (D) Linear fit of the data of 24 complex cells' onset and offset response peak latencies (solid line, $y=0.95x+8.6$, $r=0.92$; $P<0.0001$). The slope of the fit was not significantly different from 1 (*t*-test, $P=0.60$) and the intercept was not significantly different from 0 (*t*-test, $P=0.27$). Note that complex cells show more similarity in peak latencies between the onset and offset responses than that of simple cells.

and offset responses of a simple cell were spatial phase dependent as shown in Fig. 1A. In contrast, for a complex cell, both the offset transient responses and the onset responses were spatial phase independent (Fig. 1B).

Although both simple and complex cells had comparable response peak latencies of the onset and offset responses, complex cells exhibited more significant similarity in the on peak latency and the off latency than the simple cells. Fig. 1C and D showed scatter plots of peak latencies of the onset and offset responses for the simple cells and complex cells in the test trials with 100 ms stimulus on period. The linear fit (solid line) of the data showed there was a significant correlation between the on peak latency and off peak latency for the simple cells ($r=0.76$, $P<0.0001$) and complex cells ($r=0.92$, $P<0.0001$). The complex cells scattered around the line of $y=x$ more closely than the simple cells. The fit of complex cells (slope=0.95, intercept=8.6) was very similar to the line of $y=x$ ($P=0.60>0.05$, for the slope and $P=0.27$ for the intercept). In contrast, the fit of simple cells (slope=0.75, intercept=29.1) differed significantly from the line of $y=x$ ($P=0.048<0.05$ for the slope and $P=0.0081$ for the intercept).

Relative amplitude

Another difference between simple and complex cells was the relative amplitudes of the onset/offset response ratio. The simple cells (a typical example shown in Fig. 1A) usually exhibited larger amplitude in the onset response than the offset response when averaged across spatial phases. On the contrary, the complex cells (a typical ex-

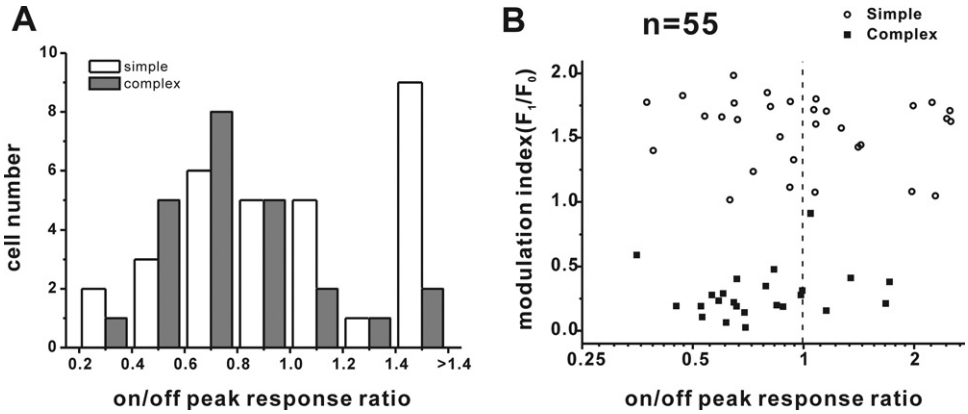

Fig. 2. Comparison of amplitudes of the onset and offset responses for simple and complex cells. (A) Distribution histogram of the ratio of the on/off peak response amplitude for all cells studied. Ratio <1 means that a cell's on peak response amplitude is smaller than the off peak response amplitude, and vice versa (mean=1.02, max.=2.52, min.=0.35). Cells having their ratios >1.4 were pooled together as shown in the right most columns. (B) Modulation index F_1/F_0 (the first harmonic Fourier component of the response elicited by a drifting grating divided by the mean response elicited by the same stimulus) plotted against the on/off peak response ratio. The ratio values for more data points of complex cells rather than simple cells were smaller than 1 (the vertical dashed line). The distributions of the on/off peak response ratio between simple cells (with modulation index >1) and complex cells (with modulation index <1) were significantly different (simple cell: 1.18±0.67, hereafter referred as a mean±S.D.; complex cell: 0.83±0.35, *t*-test, $P=0.024$), indicating that simple cells exhibited higher onset response amplitude while complex cells exhibited higher offset response amplitude. Note that the *x* axis is on a logarithmic scale.

ample shown in Fig. 1B) always exhibited larger offset response than onset response in all spatial phases. Fig. 2 shows the distribution of on/off peak response ratio for simple and complex cells (31 simple and 24 complex cells, $n=55$). The mean ratio of simple cells (1.18±0.67, hereafter referred as a mean±S.D.) was significantly larger than that of complex cells (0.83±0.35, *t*-test, $P=0.024<0.05$). Only 20.1% (5 in 24) of complex cells had on/off peak response ratio larger than 1, while 48.4% (15 in 31) of simple cells had ratio larger than 1 (Fig. 2B). Therefore, the differences were significant between simple and complex cells not only in the response peak latency but also in the on/off response ratio.

Cumulative detectability

Signal-to-noise ratio is one of the important indexes to evaluate a neuron's ability of information encoding in addition to firing rate. Cumulative detectability (for definition see Experimental Procedures) had been used as an important index to evaluate a neuron's ability to detect a stimulus (Müller et al., 2001). In the current study, detectability was measured and used as an index of signal-to-noise ratio for the onset and offset responses. Fig. 3A–D showed the time course of cumulative detectability of neurons' responses to flashing stationary gratings for four typical cells (two simple, two complex) during the stimulus on, and off period. Both the onset and offset cumulative detectability curves of each cell had similar patterns, which consisted of a rapid ascent part and a plateau. Fig. 3E shows a comparison between onset and offset response of the rising time constant (τ, the time when the curve reaches 63% (i.e. 1−1/e) of its maximal value) of cumulative detectability curves of 15 cells (5 simple, 10 complex) studied. All the data points except one were beneath the diagonal line of y=x, and on average, τ_{on} (94 ms) was statistically longer than τ_{off} (79 ms) for these accumulative detectability curves (paired *t*-test, $P=0.02<0.05$). This means that detectability of the off period increases faster than that of the on period. No obvious difference was observed between simple and complex cells in comparing the rising time course of detectability.

However, as shown by the examples, simple cells had much higher cumulative detectability in onset response than in offset response (Fig. 3A, B); while the complex cells had greater offset response cumulative detectability (Fig. 3C, D). Over all, as shown in Fig. 3F, complex cells had a much smaller detectability ratio of the onset response to offset response (0.86±0.26, mean±S.D.) than the simple cells (1.53±0.69). The difference is statistically significant (*t*-test, $P=0.02<0.05$). The remarkable higher detectability, taken together with higher amplitude in offset response, implies that complex cells are better at encoding the absence of stimuli compared with simple cells.

Stimulus duration dependence

In 12 neurons (six simple and six complex cells), incremental stimulus durations from 20 to 100 ms in a 10 ms step in a neuron's optimal orientation were randomly employed to study the influence of stimulus duration on the offset response. For the typical simple and complex cells shown in Fig. 4, increasing stimulus on period elicited a progressively increasing offset response amplitude (Fig. 4B, D, thick dashed lines) rather than the relatively constant one of the onset response (Fig. 4B, D, thin dashed lines). However, the complex cell only required much shorter minimum stimulus duration (20 ms for the complex cell) to elicit a detectable offset response compared with the simple cell (40 ms for the simple cell), and exhibited a higher off/on peak response ratio than the simple cell in each stimulus duration (Fig. 4A, C). Similar trends were observed in all the 12 neurons collected in the current study. A minimum duration of the grating stimulus is re-

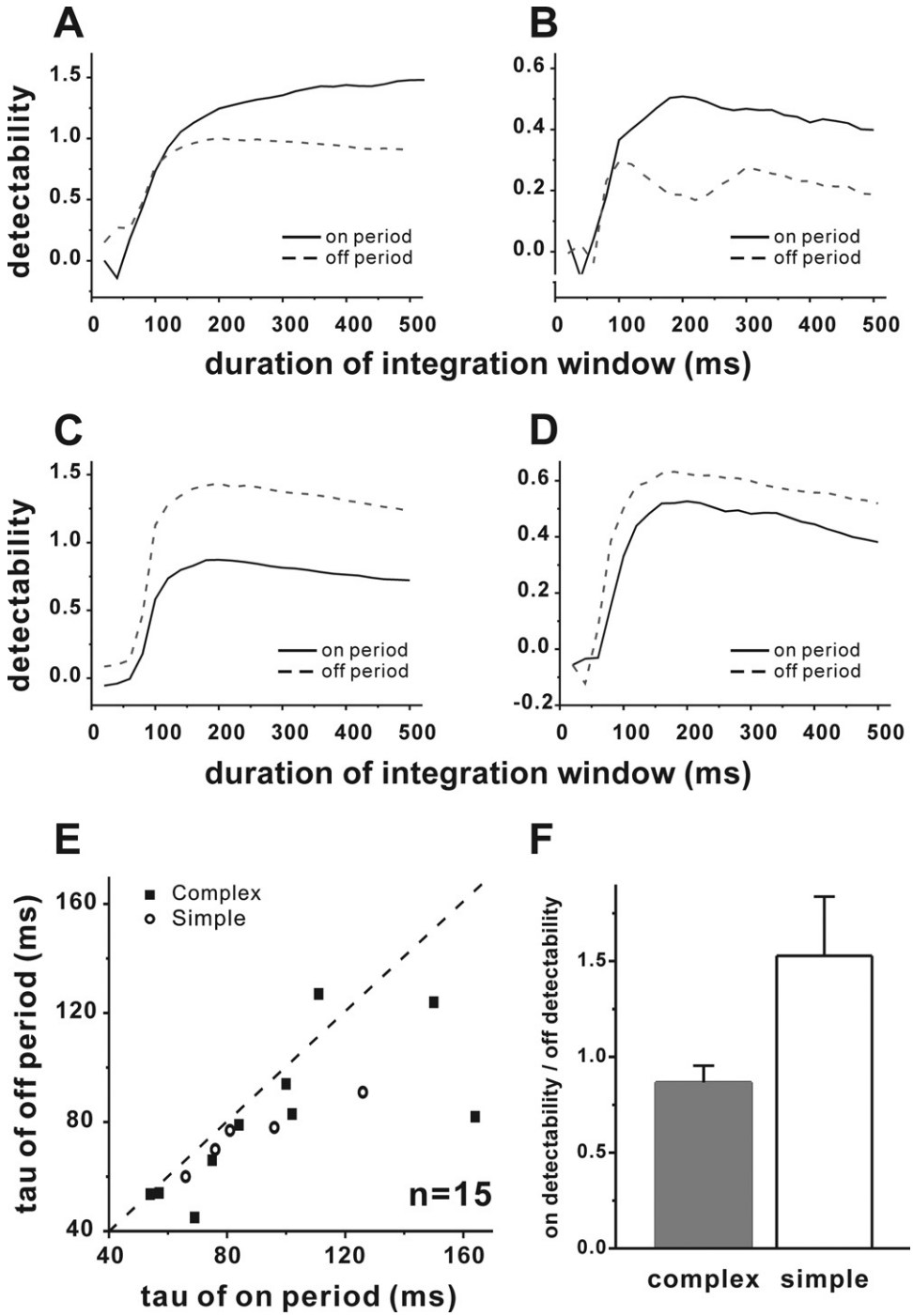

Fig. 3. Difference in cumulative detectability of the onset and onset transient responses in simple and complex cells. (A, B) Cumulative detectability curves of two typical simple cells during the stimulus on period (solid line) and the stimulus off period (dashed line). The time window integration step was 20 ms. Although the two curves had similar trends, the detectability curve of the stimulus on period saturated at a higher level than that of the stimulus off period. (C, D) Cumulative detectability curves of two typical complex cells showing that in contrast to the simple cells, the detectability was higher for the stimulus off period than for the on period. (E) Comparison of time constant (tao, τ) of cumulative detectability curves of the onset and offset responses. Note that all data points except one scatter beneath the diagonal line of y=x, indicating that the time constant of the off period was significantly shorter than that of the on period (pair *t*-test, $P=0.020<0.05$). (F) Comparison of the ratio of on/off detectability showing significant difference between the simple (five cells) and complex cells (10 cells). Overall, complex cells had a ratio of $0.86\pm0.26<1$, indicating their offset response had higher detectability than onset response; whereas simple cells behaved oppositely (ratio$=1.53\pm0.69$). Difference was statistically significant (*t*-test, $P=0.023<0.05$). Error bar: S.D.

quired to elicit an offset response for both types of cortical cells. In general, the mean of minimum stimulus duration for eliciting an offset response for the complex cell (36 ± 11 ms) tended to be shorter than that of the simple

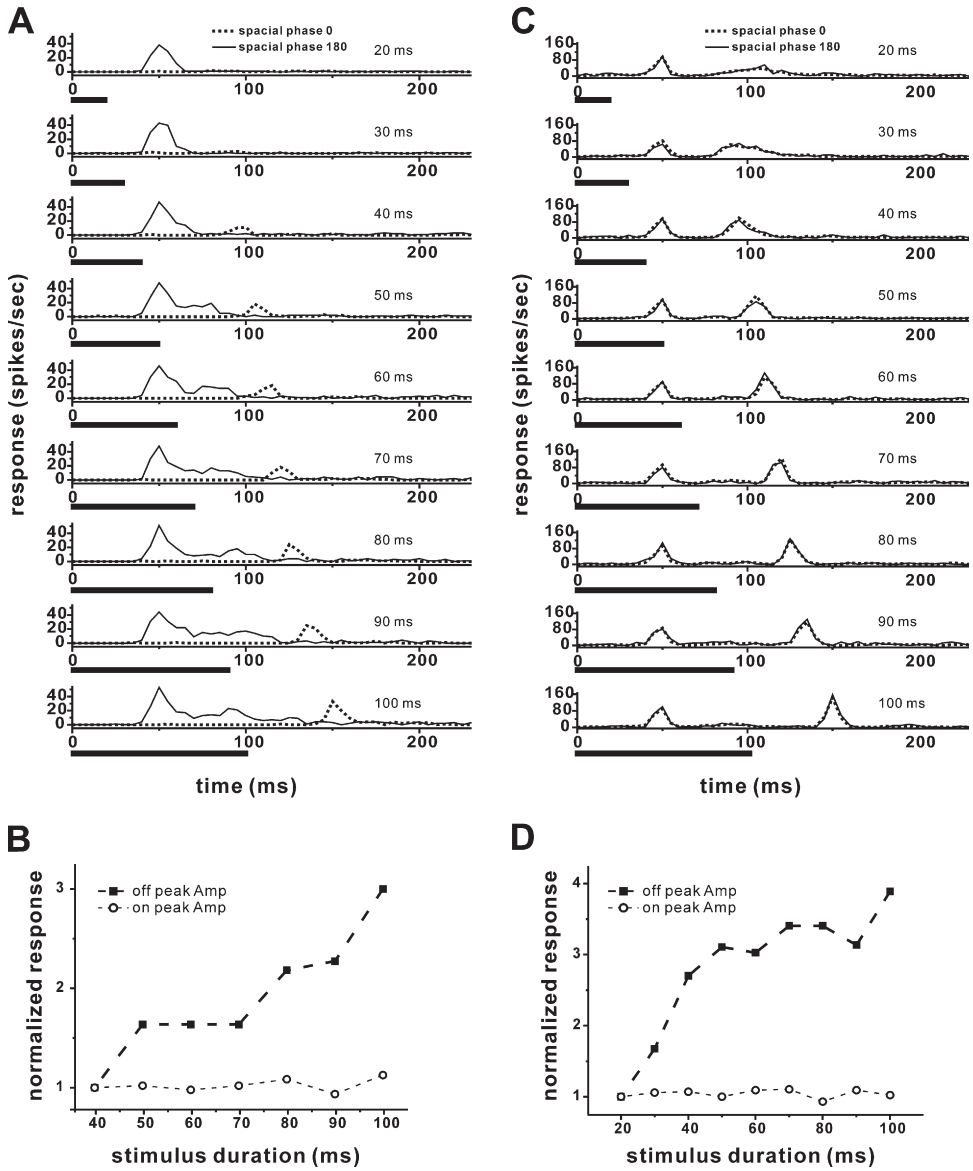

Fig. 4. Offset transient response of two types of cortical cells depending on stimulus duration (A, C) PSTHs of a typical simple cell's (A) and a complex cell's (C) responses obtained when stimulus duration increased from 20 to 100 ms in the cell's preferred orientation. Solid lines represent responses elicited by gratings at the optimal spatial phase; dashed lines represent responses at the opposite phase. Thick black bars below each PSTH indicate the duration of stimulus on period. Note that the second (offset) peak response was largely dependent on the stimulus duration, the longer the higher, compared with the greater stability of the first (onset) peak response; and the complex cell needed shorter stimulus duration (20 ms) to elicit an offset response than the simple cell (40 ms). (B, D) Comparison of the peak amplitudes of the onset response (thin dashed line) and the offset response (thick dashed line) in different stimulus duration test trials of the simple cell (B) and complex cell (D). The onset and offset responses were normalized to those in the 40 ms stimulus duration test trial for the simple cell, and to the 20 ms stimulus duration test trial for the complex cell, respectively. Note that the response amplitude of the offset response increased more rapidly for the complex cell than for the simple cell.

cell (46±5 ms) though the difference between them was not statistically significant due to less samples (*t*-test, $P=0.12$). This might imply a possibility that the offset responses of simple and complex cells are originated differently, but further study remains to be done before drawing a conclusion. Furthermore, the relative amplitude of offset response of the complex cell also rose faster than the simple cell as stimulus duration increased (compare thick dashed lines in Fig. 4B and D). As long as the duration was long enough, the peak amplitudes of the offset response reached a plateau in both types of cortical cells. Overall, the offset transient response was affected significantly by changing duration of the stimulus.

DISCUSSION

In this study, we found that the offset transient response of complex cells had several different aspects compared with

simple cells, in addition to spatial phase independence. The peak latencies of the onset and offset responses of complex cells seemed almost identical, but this was not true for the simple cells. The complex cells preferred to encode the stimulus absence due to their higher offset response amplitude and detectability, while the simple cells tend to signal the presence of the stimulus more than its absence due to their higher onset response amplitude and detectability. The complex cells could be evoked to produce an offset response by shorter stimulus presenting duration than the simple cells.

Difference between simple and complex cells

The spatial phase independence in the offset response of complex cells in this study can be easily explained using Hubel and Wiesel's (1962, 1968) hierarchical model when considering convergence of the offset response inputs from several simple cells which have different spatial phase preference. We found that on average, simple cells had the onset response amplitude higher than that of the offset, but complex cells had the offset response amplitude higher than the onset. This may lead one to imagine that there may be a mechanism that selectively amplifies the offset response along the convergent path from simple cells to complex cells. However, it is still hard to interpret how convergence can make the response that is variable and late at the preceding stage, become more consistent and faster at the next stage, considering that the peak latencies and minimum stimulus duration to elicit an offset response are shorter in complex cells than in simple cells, as well as the signal-to-noise ratio (evaluated as detectability here) of offset response is lower in simple cells.

In fact, Hubel and Wiesel's (1962, 1968) hierarchical model may not be an exclusive one because it cannot explain many results, such as the disappearance of cortical neurons' orientation selectivity induced by GABA antagonist (Creutzfeldt et al., 1974; Sillito, 1975; Sillito et al., 1980; Pei et al., 1994) and the contrast invariance of orientation selectivity in simple cells (Troyer et al., 1998; Shapley et al., 2003). In addition, using a functional optical imaging guided retrograde HRP labeling method Zhan and Shou (2002) provided the first anatomic evidence for the model for 40 years and pointed out the model may not be a common one, even rare in fact.

It was found that some complex cells receive monosynaptic input from the thalamus, and a parallel model was proposed that simple and complex cells receive predominantly projections from the X- and Y-type cells in the cat's LGN respectively (Hoffmann and Stone, 1971; Stone et al., 1979; Orban, 1984). Most simple cells that respond linearly may mainly receive input from linear X cells, and complex cells that respond nonlinearly from nonlinear Y cells (Movshon et al., 1978a,b). In addition, it has been proven by modeling that unoriented 'center-surround' antagonistic LGN input can generate complex-like phase-invariant orientation tuning (Mel et al., 1998). Recent work of our laboratory was consistent with the parallel model. Simple cells in the cat's area 17 were affected more significantly than complex cells by a brief elevation of intraocular pressure (IOP) (Chen et al., 2005), which was in agreement with the findings that X type of retinal ganglion cells and LGN relay cells were also more sensitive than the Y cells in the cat to brief elevation of IOP (Shou and Zhou, 1989, 1990; Zhou et al., 1994; Chen et al., 2005). It is well documented that Y cells in the cat's subcortical pathway are well characterized by nonlinear summation (such as frequency doubling or strong on- and off-response to flashing gratings), fast conduction velocity and transient response; while X cells are linear, slower and sustained (Enroth-Cugell and Robson, 1966; Cleland et al., 1971). Therefore, overall, it is safe to think that at least in cats, different components of the X and Y inputs might contribute differentially to the offset responses in simple and complex cells.

However, the cortico-cortical connections cannot be neglected in regard to contribution of forming the simple- and complex-like responses of cortical neurons, because the recurrent excitatory synapses outnumbered the LGN excitatory synapses in visual cortex (Peters and Payne, 1993). Model simulation studies showed that the balance between LGN feedforward input and cortico-cortical recurrent can determine whether a cortical neuron behaves as a simple cell or complex cell (Chance et al., 1999; Tao et al., 2004). Recently, it has been proposed that simple and complex cells might not be distinct cell types when regarding their intracellular modulation instead of the conventional spike rate modulation (F1/F0 ratio) (Mechler and Ringach, 2002; Priebe et al., 2004). Intracellular recording of subthreshold membrane potential and spikes provided experimental evidence that spike-threshold non-linearity might be the underlying mechanism (Priebe et al., 2004). Furthermore, more recent study showed that decreasing stimulus contrast or adapting to high contrast, which was assumed to bring membrane potential down toward spike-threshold, increased the F1/F0 ratio of complex cells, in agreement with the spike-threshold hypothesis (Crowder et al., 2007). It was also shown that exciting the suppressive surround or inactivating excitatory feedback from higher order cortex could turn substantial portion complex cells into simple-like cells (Bardy et al., 2006). Whether cortical recurrent circuitry contributes to the difference between the simple and complex cells in offset responses found in this study is an open question and needs further investigation.

Duration dependence of the offset transient response

In our study, for both simple cells and complex cells, a minimum duration of stimuli (about 30–50 ms) was required to evoke a significant offset response, and within the range of 100 ms tested, the longer the duration, the larger the response. Similar duration dependence of the visual responses has been well-documented in the literature either for the on-response in ganglion cells (Levick and Zacks, 1970) and cortical cells (Duysens et al., 1985, 1991), or for the off response in the ganglion cells (Enroth-Cugell and Pinto, 1972), LGN cells (Brooks and Huber, 1972) and cortical cells (Duysens et al., 1996). Although the experimental methods and stimulus durations used by those authors were varied, the mechanisms underlying the

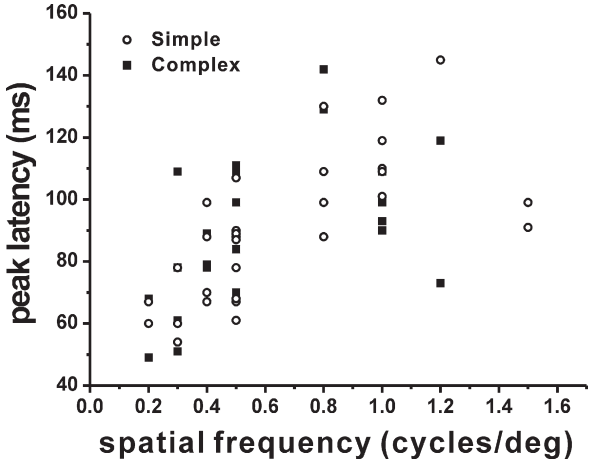

Fig. 5. Correlation of peak latency and optimal spatial frequency of the offset responses in simple and complex cells. Data of 31 simple cells and 24 complex cells showed a significant positive correlation between peak latency of the offset transient response and optimal spatial frequency for each cell (simple cell: $r=0.67$, $P<0.0001$; complex cell: $r=0.50$, $P=0.013$).

off response were referred to interaction between excitation and disinhibition. Furthermore, Duysens et al. (1996) reported that this 'increment' behavior was only seen in Y-off type geniculate cells and that off responses of some cortical cells showed significant duration tuning which was never seen in the LGN, suggesting that the duration dependence of the off response of cortical cells differs at least partially from that of the LGN relay cells in the cat, and might involve intracortical mechanisms. Since intracortical GABAergic inhibition could strongly lower cortical neurons' spontaneous activity and visually driven response, we speculated that during a brief stimulation in our study, the cortical cells receive the combination of excitation and inhibition followed by disinhibition at offset, which are both duration dependent and balanced by the local neural network. Thus, the longer the stimulus duration, the larger the disinhibition at stimulus offset, which could cause a larger offset response.

Possible significance of the offset transient response

Psychophysical studies found that a brief visual stimulus is often perceived to last much longer than its presenting duration for human subjects. Bowen et al. (1974) reported that the visual persistence was constant up to 100 ms for equal-energy flashes. Meyer and Maguire (1981) found that both stimuli of 50 ms and 250 ms durations of a grating could generate persistence of about 250 ms. The parameters they used in their experiments were similar to those used in this study. Although different experimental methods and/or instructions to subjects could cause different results concerning duration of persistence, the offset transient response shown here lasted on a comparable time scale, i.e. on average, peaked at 90 ± 23 and 89 ± 24 ms after the offset of a stimulus for the simple and complex cells, respectively.

In addition, it was reported that the duration of visual persistence related directly to stimulus spatial frequency (Meyer and Maguire, 1977) and suggested that the transient channels which are more sensitive to lower spatial frequencies have faster dynamic response, hence, shorter persistence. Similarly, we also found a significant positive correlation between the peak latency of the offset transient response and the stimulus spatial frequency for both the simple cells ($r=0.67$, $P<0.0001$) and complex cells ($r=0.50$, $P=0.013$), as shown in Fig. 5. It is reasonable to speculate that if the offset responses of cortical cells in area 17 that were found in anesthetized animals also exist in awake animals, this rebound offset response of cortical cells to disappearance of a pattern might presumably contribute to visual persistence in humans.

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