

Plasticity of the landing response of *Drosophila melanogaster*

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Summary. Fruitflies (*Drosophila melanogaster*) may respond with landing reactions in tethered flight to unilateral progressive motion of single vertical dark stripes. The response frequency to repeated unilateral stimulation has a characteristic time course, a fast increase followed by a slower decrease. This behaviour is explained by the habituation of the input channels to a leaky integrator. The half-life of the integrated signal is in the range of 1 s. 'Contralateral sensitization' (CoS) describes the sensitization of the landing response to unilateral stimuli by preceding contralateral stimulation. It acts by increasing the initial reactivity, which habituates. The effects of CoS are thus still obvious after 1 min of repetitive stimulation. CoS can effectively be mediated by movement stimuli as well as by flickering light. We also show that binocular rotation rather than unilateral back to front motion inhibits the landing response (in the monocular part of the visual field). The biological significance of the described temporal characteristics of the landing response system and their possible neuronal basis are discussed.

Key words: Habituation – Contralateral sensitization – Leaky integrator – Rotation detectors

Introduction

Flies are able to end their flight smoothly by landing manoeuvres which involve movements of all legs. While the middle and hind legs are lowered and spread, the front legs are stretched and raised above the head (Goodman 1960). The landing response can be elicited in stationary flight by visual stimuli which simulate the approach towards an object. One line of interest in the past decades has been in the analysis of the relevant visual parameters. Braitenberg and Taddei-Ferretti (1966) as

well as Taddei-Ferretti and Perez de Talens (1973) showed that movement detection plays the most important role. Borst and Bahde (1986) characterized the movement detectors triggering the landing response and found that they are similar and may be physically identical to those used in the optomotor response. Their outputs feeding the landing response are spatially and temporally summed by a leaky integrator. A threshold device then determines whether landing occurs or not (Borst and Bahde 1987, 1988; Borst 1989; Rees and Spatz 1989).

Another line of interest considered the landing response as a means to study habituation (Fischbach 1981; Wittekind and Spatz 1988; Fischbach and Bausenwein 1988; Rees and Spatz 1989) and sensitization (Fischbach 1981, 1983; Wittekind 1987). These plastic properties of the landing response have so far systematically been studied only in *Drosophila*, although at least habituation occurs under appropriate stimulus conditions in larger Diptera as well (Wittekind 1987; A. Borst, personal communication). It is now well established by experiments studying the transfer of habituation between different parts of the visual field that the habituating neurons have relatively small receptive fields, i.e. habituation of the landing response occurs at a level of sensory integration at which the retinotopic projections are still fairly fine grained (Fischbach and Bausenwein 1988). On the other hand, habituation does not occur at the level of the retina or even lamina, as it was found that the receptive field sizes of habituating units differ for movement from front to back and for upward movement. This suggests that the habituating neurons are directionally selective, a conclusion which has been confirmed in a recent study of Wittekind and Spatz (1988).

In this paper we present a detailed analysis of the dependence of the landing response probability on stimulation history. We show that its time course during uniform repetitive stimulation can be explained by habituation of the input channels of a leaky integrator. We also show that contralateral sensitization (Fischbach 1981) is not selective for the direction of motion and that

Abbreviations: CoS contralateral sensitization

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it can be mediated by flickering light. In addition, we found that inhibition of the landing response is mediated by a detector for bilateral turning stimuli (a rotation detector). The results are integrated into a minimal model of the landing response system of *Drosophila*.

Materials and methods

Stocks and preparation of flies. All experiments were performed with 3-day-old females of the *Drosophila melanogaster* wild-type strain Berlin (Jacob et al. 1977). One day before testing, a small wire was glued with wax between their head and thorax (Götz 1964), which had been immobilized in cold air.

Experimental procedures. Flies were kept in stationary flight in front of a monitor (Tektronix 606). Stimuli were produced by a pattern generator (200 images/s; constructed by J. Blondeau) controlling position, orientation and movement of two dark objects. In our experiments the flies were stimulated either by single, vertically oriented, dark stripes moving from front to back (progressive) or from back to front (regressive) or by flicker stimuli (square wave).

Stimuli were presented unilaterally (from $\pm 18^\circ$ to $\pm 41^\circ$) in a 23° wide and 64° high section (from -32° below to $+32^\circ$ above the equator of the eye) of the frontal monocular visual field. The starting position of the moving stripes at the borders of the binocular field of view were covered with a 9° wide black mask on each side (extending from $+8^\circ$ to $+17^\circ$ and from -8° to -17° , respectively). In front of the fly the stripe was 8° wide and 64° high. It moved at a mean angular velocity of $130^\circ/\text{s}$. The flicker stimulus was presented in the same visual field by switching the screen from bright to dark with the dark phase lasting for 60 ms/cycle, the bright phase for 1940 ms/cycle. The temporal frequency of stimulation was constant and the same in all experiments (0.5 Hz) with the exception of the RANDOM experiment (see below), so that the different stimuli were roughly similar for a single receptor cell.

All experiments with the exception of the RANDOM experiment (see below) were composed of several alternating stimulus phases (I–V). The first side of unilateral stimulation was determined by a random number generator. In each phase a sequence of 32 equal stimuli was given with a frequency of 0.5 Hz. In the first, third and fifth phases the stimuli were always of the same mode. Stimuli with another, but uniform mode could be presented in the intermediate phase II and IV.

In the RANDOM experiment, left and right unilateral progressive stimuli were given alternately. The interval between the start of each pair of stimuli was randomly varied between 300 and 4650 ms. Tests were continued until flies stopped flying or did not show any landing during 1 min.

Data evaluation. To record the landing response, a red light image of the fly was projected through a microscope onto a screen (Erber and Schildberger 1980; Wittekind 1987). The extension of the front legs in front of and above the head was monitored by means of a light guide which was mounted to that screen at an appropriate position.

Although the landing response of *Drosophila* is a graded response, it was recorded as an all-or-none reaction by only counting a response as positive if the light guide was shadowed by the front legs. The presentation of stimuli and the recording of the landing response was controlled by an Apple II computer. Only such flies were used for averaging which did not stop flying throughout the duration of the experiment. This measure was necessary because short flyers are bad landers (data not shown).

If not otherwise stated, significance levels given in the text were determined by a statistical test for comparison of two Bernoulli probabilities (Precht 1982). The χ^2 test of goodness-of-fit was used to compare experimental frequency distributions with theoretical ones (Pollard 1977).

Results

Time course of the response frequency during repetitive stimulation

When stationary flying *Drosophila* are stimulated by front to back motion of a single vertical black bar, the probability of eliciting the landing responses shows a strong dependence on the repetition of the stimulus. Under our experimental conditions (i.e. the usage of weak stimuli) only about 50% of the flies showed a landing response to the first stimulus. The landing response to the second stimulus presented 2 s later is significantly increased by about 25% (see Table 1). Thereafter, the proportion of flies responding to additional stimuli (presented at 0.5 Hz) decreases steadily with the number of repetitions (Fig. 1). It has been shown previously that this reflects true habituation and not fatigue of the landing response (Fischbach 1981, 1983; Fischbach and Bausenwein 1988; Wittekind and Spatz 1988).

We wondered whether the initial increase in the landing response probability is the consequence of temporal integration of successive stimuli. We therefore tested the performance of the following simple model:

Table 1. Landing response frequencies in response to the two first stimuli

Response	No. of flies	Percentage ¹	Calculated ²	Calculation
Landing to first	90	49.2 \pm 3.7	49.2 ³	100 p_1
Landing to second	138	75.4 \pm 3.2	75.4 ³	100 p_2
Only to first	15	8.2 \pm 2.0	12.7	100 $p_1(1 - p_2)$
Only to second	63	34.4 \pm 3.5	37.7	100 $(1 - p_1)p_2$
To both stimuli	75	41.0 \pm 3.6	36.5	100 p_1p_2
To none	30	16.4 \pm 2.7	13.1	100 $(1 - p_1)(1 - p_2)$

¹ The percentage-error is calculated using the \sqrt{n} -rule and the Gaussian error continuation formula

² The assumption underlying the calculation implies that the landing response probability to the second stimulus is not influenced by actual landing to the first stimulus. The experimentally determined response frequencies for the first and second landing (p_1 and p_2) can thus be used to calculate the double event probabilities. The good agreement of these probabilities (fourth column) with the actual double event frequencies (third column) shows that the assumption is right

³ These are the experimentally determined response frequencies p_1 and p_2 , respectively

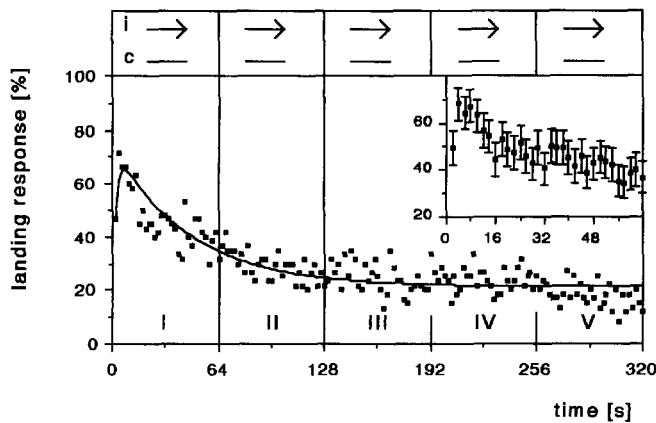


Fig. 1. Landing response frequency (%) of 58 female flies during the presentation of 160 progressive stimuli in the frontal part of the monocular visual field of one eye. The stimulated eye was randomly selected for each fly at the beginning of the experiment. The continuous line is a theoretical description of the time course of responsiveness (see text). The parameters used for the theoretical description have been derived from an optimal fit of the model to the data. The subdivision of the graph into 5 periods is for better comparison with Figs. 2–5, 7. In the insert the landing response frequencies of 183 flies during the presentation of 32 successive progressive stimuli are shown. These data are the pooled results of time periods I in Figs. 1–5. The error bars denote the Bernoulli interval of confidence (Precht 1982). The response frequency to the very first stimulus is significantly lower than that to the second stimulus. The arrows above the graph indicate the direction of motion in each period (progressive +; regressive –); a bar indicates no stimulation; i and c stand for ipsilateral and contralateral eye, respectively

The output of a leaky integrator after the n^{th} stimulus (y_n) is supposed to be proportional to the landing probability in response to that stimulus (this assumption seems plausible since the stimuli delivered were near threshold; Rees and Spatz 1989). This y_n is the sum of a fraction of the previous filling state of the integrator (αy_{n-1} , with α defining the degree of leakiness) and of the stimulus strength, $x_n + x_c$. The fraction of the stimulus strength which does not habituate is x_c . Due to habituation, the input x_n is only a fraction of the previous input ($x_n = \beta x_{n-1}$, with β as habituation factor). These assumptions lead to the following simple recursive equation:

$$y_n = \alpha y_{n-1} + x_n + x_c \quad (1)$$

with $x_n = \beta^{n-1} x_1$ this reads

$$y_n = \alpha y_{n-1} + \beta^{n-1} x_1 + x_c \quad (2)$$

Using the starting condition $y_0 = 0$, a least square fit of this function to the experimental data in Fig. 1 determines the parameters as follows:

Leakiness factor $\alpha = 0.25$

Habituation factor $\beta = 0.96$

Strength of first stimulus $x_1 + x_c = 0.51$

with $x_1 = 0.35$ and $x_c = 0.16$.

The leakiness factor $\alpha = 0.25$ describes the decay of the integrated signal in 2 s. Assuming an exponential function, this means that the integrated signal decreases in 1 s by 50%.

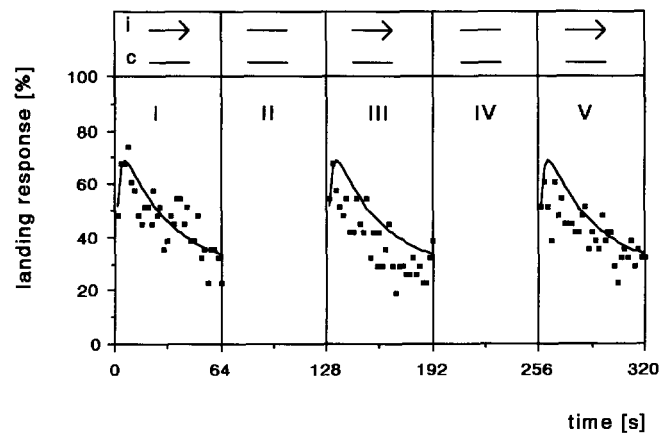


Fig. 2. Spontaneous recovery. The data points in periods I, III and V show the landing response frequency (%) of 37 flies during stimulation with progressive stimuli (32/period). In periods II and IV no stimuli are presented, which leads to a significant recovery of the response. The theoretical curves have been fitted to the data of period I using the same model as in Fig. 1 and the assumption that during periods II and IV complete recovery has taken place. Actual recovery is not complete

The theory assumes that actual landing does not empty the integrator. This was directly confirmed by looking at the landings of individual flies in response to the first two stimuli. It was found that the probability of landing to the second stimulus was even slightly, albeit not significantly, higher in flies with a response to the first stimulus (see Table 1; compare entries for only to second and for to both stimuli).

Recovery of the landing response in the absence of stimuli

In Fig. 2 it is shown that the landing response recovers significantly in the time periods II (64–128 s) and IV (192–256 s) in which no stimuli are given. The mean landing response activities in time periods I (0–64 s), III (128–192 s) and V (256–320 s) are $49.9\% \pm 2.3\%$, $41.2\% \pm 2.3\%$ and $44.4\% \pm 1.7\%$, respectively. The recovery is not due to a revival of the motor system (Fischbach 1981; Wittekind and Spatz 1988).

Unilateral stimulation sensitizes the response to contralateral landing stimuli

If after 32 stimuli (corresponding to 64 s) repetitive movement from front to back is switched from one monocular side to the other, the landing responses are strongly sensitized. This phenomenon of contralateral sensitization (CoS) has been reported previously (Fischbach 1981, 1983; Fig. 38 in Heisenberg and Wolf 1984). CoS is evident not only by recording the frequency of landing responses (Fig. 3), but also by measuring response latency and observing response duration. In the sensitized state the front legs of the flies may remain extended and lifted above the head until the next stimulus

arrives (i.e. for about 2 s), while in the normal or partially habituated state landing in response to the moving stripe is more like a brief and transient flip of the legs into the landing position.

The CoS effect in Fig. 3 can well be described by using in Eqn. (2) for $65 > n > 32$ instead of x_1 the habituable contralateral stimulus strength, x_{1c} . The degree of CoS is $S = x_{1c} - x_1 = 0.33$. The lower responsiveness in periods

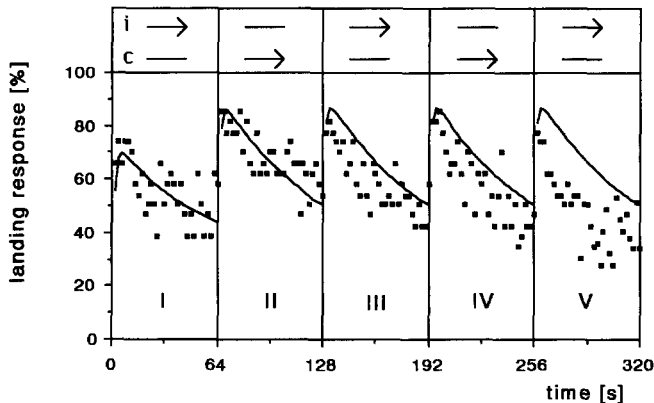


Fig. 3. Contralateral sensitization. The points show the landing response frequency (%) of 30 flies during stimulation with 160 unilateral progressive stimuli. After 32 stimuli each, stimulation is switched to the contralateral visual field. This strongly sensitizes the landing response. An independent set of data showing the same phenomenon (using 116 flies, manual recording and a stimulus frequency of 0.36 Hz) has been published elsewhere (Fischbach, as cited in Fig. 38 of Heisenberg and Wolf 1984). The continuous lines describe the behaviour of the same model as in Fig. 1 assuming that after contralateral progressive motion the input channels are sensitized (see text). The theory has been fitted to the data of periods I and II. The habituation factor used (0.97) is the same throughout. The integrator is not reset after switching

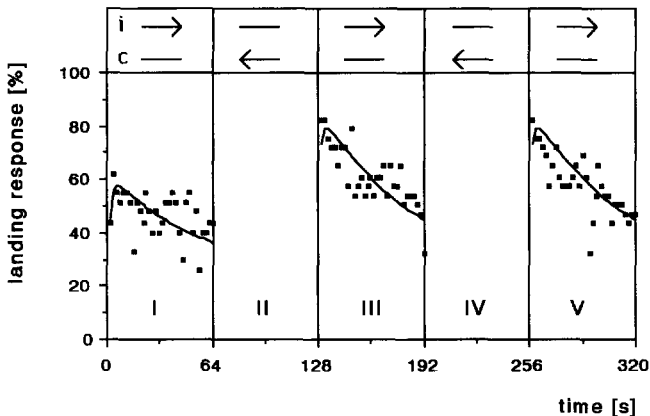


Fig. 4. Sensitization by regressive motion. The points in periods I, III and V show the landing response frequency (%) of 26 flies during stimulation with progressive motion. In the periods II and IV the corresponding area of the contralateral eye is stimulated by regressive motion (using otherwise identical parameters). The landing response thereafter is sensitized as shown in periods III and V. The continuous lines describe the behaviour of the same model as in Fig. 1 assuming that after contralateral regressive motion the input channels are sensitized. The habituation factor used (0.97) is the same throughout. The integrator is not reset after switching. A basic level of landing responses to regressive motion of about 10% was observed

III–V can come about by incomplete recovery (see also Fig. 2) and by a decrease in the effect of repeated CoS.

Contralateral sensitization is insensitive to the direction of motion

CoS demonstrates the existence of an interocular cross-talk. At what level does this crosstalk take place? Are the neurons mediating it sensitive to the direction of motion? The answer to this question will be important because all bilaterally arborizing tangential neurons connecting both lobula plates described so far are directionally sensitive (Hausen 1981), while similar evidence for medullar tangential neurons is missing. Therefore, we replaced the contralateral progressive stimuli in time periods II and IV of our experiments by contralateral regressive motion (Fig. 4). It can be clearly seen that the landing response thereafter (in periods III and V) is sensitized at least as strongly as by progressive motion (Fig. 3). The effect of CoS in periods III and V of Fig. 4 is best described by assuming an S value of 0.55. Therefore, the direction of movement is not important for the elicitation of CoS.

Contralateral sensitization is mediated by flicker

Although at the level of the medulla activity labeling using the 2-deoxyglucose method has not yielded any evidence for directional sensitivity (Buchner et al. 1984; Bausenwein 1988), medullar neurons clearly display movement-sensitive activity. The same authors, however, did not find any evidence for movement sensitivity in the first optic neuropil, the lamina. It is known from electrophysiological studies that this neuropil is sensitive to flicker (Laughlin 1980). Therefore, replacing regressive

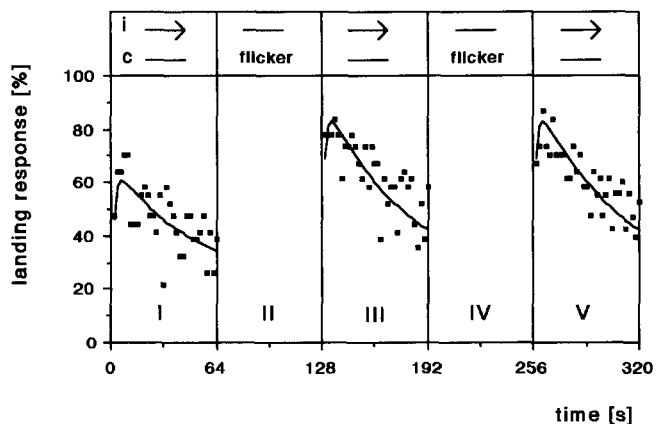


Fig. 5. Sensitization by flicker. The points in periods I, III and V show the landing response frequency (%) of 32 flies during stimulation with progressive motion. In periods II and IV the corresponding area of the contralateral eye is stimulated with flicker. The landing response is sensitized by flicker as shown in periods III and V. The continuous lines describe the theoretical behaviour of the same model as in Fig. 1 assuming that after contralateral flicker the input channels are sensitized. The habituation factor used (0.97) is the same throughout. The integrator is reset after switching. Landing responses to the flicker stimuli were below 5%

motion by flicker stimuli in our standard experiment might yield useful information about the neurons mediating CoS. The results (Fig. 5) show that flicker is indeed sufficient for sensitization. The effect of CoS in periods III and V is best described by assuming an S value of 0.49. We conclude that the neurons mediating CoS are flicker-sensitive.

It is worthwhile to note that the slopes of the experimental habituation curves in Figs. 3–5 differ before and after CoS. This is theoretically described without changing the habituation factor or the leakiness. It simply results from the increased initial stimulus strength after CoS and is a consequence of the exponential nature of the habituation curves. The long duration of CoS thus also finds a simple explanation: it simply is a consequence of the habituation factor.

Direct determination of the integrator's leakiness

CoS provides the opportunity to measure the leakiness of the integrator directly. When single, unilateral, progressive stimuli are given alternately in the right and in the left visual field, the stimulus interval can be randomly varied. Thus, the frequency of the landing response to S_2 can be investigated as a function of Δt , the time elapsed since the start of the pre-stimulus S_1 . While contralateral sensitization keeps the landing response frequency high over a significant amount of time, its long-lasting nature makes its interference with the measurement of the characteristics of stimulus integration negligible.

In this RANDOM experiment (see Materials and methods) the landing response frequency to S_2 decreases with an increasing Δt between S_1 and S_2 until a plateau value is reached. The 50% level of the maximal effect of S_1 on the response to S_2 is reached at about $\Delta t = 1$ s (Fig. 6). This is in good agreement with the half-life of the integrated signal as determined by the curve fit to the data in Fig. 1.

The landing response is inhibited by bilateral turning stimuli

It has been reported repeatedly in the literature that regressive motion inhibits the landing response in large flies (Eckert et al. 1979; Eckert and Hamdorf 1980; Borst 1989). On the other hand, we have shown in this paper that unilateral regressive motion sensitizes the landing response in *Drosophila*. How can these results be reconciled? We suggest that it makes a difference whether regressive motion is a component of a bilateral rotatory stimulus or not. This conclusion is based on the data shown in Fig. 7. In our experimental set-up, a bilateral rotatory stimulus is not very effective in eliciting the landing response, although it does contain the progressive stimulus component on one side (Fig. 7, time period I). This seems to indicate an inhibition of the landing responses to progressive movement by *simultaneous* regressive movement on the contralateral side. However, when regressive stimulation is stopped in period II, the

landing response frequency remains relatively low initially. Such a persistence of the inhibition is surprising as no indication of it is seen after regressive motion alone (see Fig. 4). We have to conclude that the bilateral rotatory stimulus has a different quality than unilateral regressive movement alone. It is only in the second half of period II that the inhibitory after-effect has faded away. Most interestingly, the recovery leads to sensitized levels of the landing response frequency. Landing in period II in Fig. 7 (curve 2 in Fig. 8) is significantly ($P < 0.001$) more frequent than in period II in Fig. 1 (curve 1 in Fig. 8). Therefore, although after the stop of regressive motion CoS is initially overruled by the after-effect of inhibition, this after-effect fades quickly, and it becomes evident that CoS did take place. In Fig. 8 the level of sensitization of the landing response after 32 contralat-

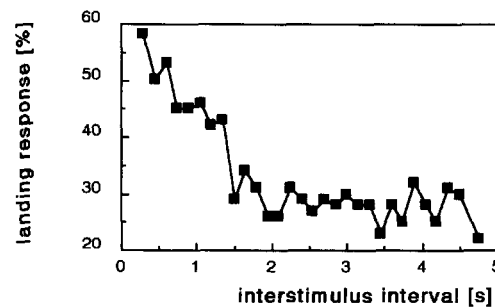


Fig. 6. The landing response frequency to a progressive stimulus S_2 is plotted against the time passed since a contralateral progressive stimulus S_1 . The experiment was performed as described in Materials and methods. The data show that the response frequency decreases with an increasing stimulus interval. The inferred half-life of the integrated S_1 -signal is about 1 s. This corresponds very well with the leakiness of the integrator as determined from the data of Fig. 1

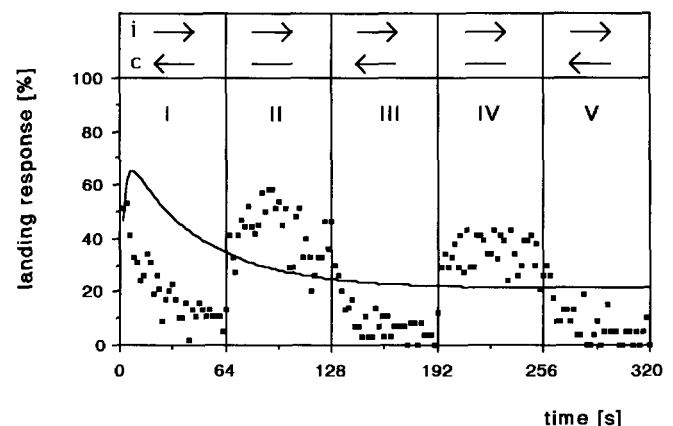


Fig. 7. Bilateral rotatory stimuli inhibit the landing response: 34 test flies were stimulated unilaterally by progressive motion of a single black stripe. Stimulation on the contralateral eye was varied. In periods I, III and V a regressively moving stripe was shown in phase with the progressively moving stripe. This produced a binocular rotation stimulus which was only slightly effective in eliciting the landing response. In periods II and IV only the monocular progressive stimulation was maintained. The continuous lines describe the theoretical behaviour using the same model and parameters as in Fig. 1 and the assumption that the regressive stimulus component in periods I, III and V has no effect

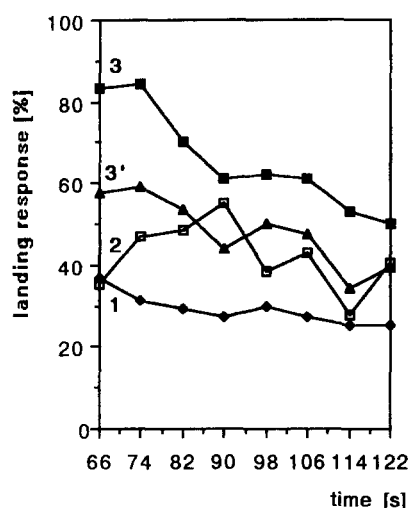


Fig. 8. Landing response frequencies to unilateral progressive stimuli (each point shown is the mean of the responses to 4 stimuli presented in sequence). Curve 1 shows the landing response frequency after 32 ipsilateral progressive stimuli (data from period II in Fig. 1). Curve 2 shows the landing response frequency after 32 bilateral rotation stimuli (data from period II in Fig. 7). Curve 3 shows the landing response frequency after 32 contralateral regressive stimuli (period II of an independent experiment). Curve 3' has been obtained from curve 3 by subtracting the amount of habituation taking place during 32 unilateral progressive stimuli. The Δ -values for subtraction were obtained using the data in Fig. 1, i.e. $\Delta_{32+i} = f_i - f_{32+i}$ where f_i is the landing response frequency at stimulus no. i . The data show that inhibition of the landing response by the bilateral rotation stimulus fades faster than contralateral sensitization

eral regressive stimuli is included (curve 3). When, for a better comparison with curve 2, curve 3 is corrected to curve 3' by taking into account the habituating effect of 32 additional progressive stimuli, a good match is obtained after the fading of inhibition by the rotatory stimulus.

Discussion

The dependence of the landing response on stimulation history is due to plastic properties of several components of the underlying information processing system. We have presented evidence for integration, habituation, sensitization and long-lasting inhibition. These phenomena will be discussed separately.

Temporal integration of landing response signals

In our experiments stimulus strength was adjusted to obtain a landing response frequency of about 50% at the very first stimulus. An interesting observation was that flies responded much better to the second stimulus. This corresponds to the finding of Wittekind (1987) that the response latency of *Drosophila* to the first landing stimulus is longer than to the following ones. Rees and Spatz (1989) excluded the first stimulus as a special case from their theoretical description of habituation curves. A

possible explanation for the initial rise in responsiveness is offered by an experiment using *Musca*: Borst and Bahde (1988) have shown that subthreshold stimuli decrease the landing response latency to subsequent stimuli. They explain their results by assuming that an integrator is partially filled by the subthreshold stimulation. The high response to the second landing stimulus (Fig. 1, Table I) indicates that such an integrator also exists in *Drosophila*. We therefore varied the time interval between two subsequent stimuli and found that they are indeed summed by a leaky integrator (Fig. 6). The half-life of the integrated signal of about 1 s is compatible to the finding of Borst (1989) in *Musca*, who describes significant effects of stimulus S_1 on the response latency to S_2 , even if the stimuli were separated by 1 s.

Why does the landing response habituate?

After the initial rise of the landing response frequency, it decreases steadily. The theoretical description of this behaviour requires habituation of the input channels of the landing signal integrator. What is the biological significance of this behaviour?

In normal flight, the fly will experience a flow of bilateral progressive motion. While it is essential for the course control system that it does not habituate – otherwise visual guidance of long straight flights in an evenly textured surround would be impossible – the input channels to the landing signal integrator should switch themselves off if stimulation is weak and repetitive. Otherwise the integrator would eventually be filled, and a landing response would occur in mid-air. Leakiness of the integrator does not seem to be sufficient to prevent such a disaster in response to unavoidable weak stimuli.

How specific is contralateral sensitization?

CoS has to be added to the simple model of the landing response system described in the first section. It is not sufficient to assume that after switching sides, new unhabituated input channels are used to feed an already partially filled integrator (due to its leakiness, this effect fades very quickly). Rather, a long-lasting sensitization of the input channels has to be assumed. Due to its side-specificity, this sensitization cannot act after both unilateral landing response pathways have merged. Therefore, we suggest that sensitization acts directly on the habituating synapses (Fig. 9). Detailed information about the retinotopic organization of the sensitizing channels is not yet available.

Theoretically, the CoS effect was best mimicked by assuming an increase in the initial stimulus strength alone. CoS did not change the habituation factor. Due to their exponential nature, the increase in the slopes of the habituation curves after CoS is due to their higher starting values. Such an effect of CoS is compatible with very simple cellular models of habituation and sensitization (Kandel 1981), e.g. it would be sufficient to assume

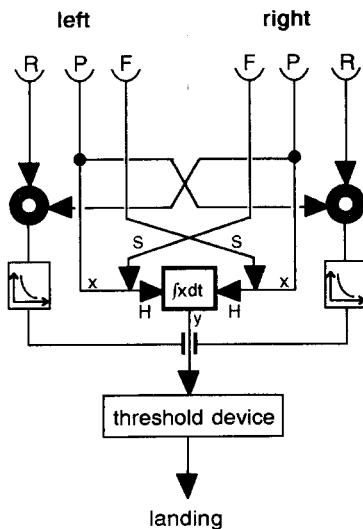


Fig. 9. Model of the landing response system integrating the results presented in this paper. Arrays of progressive movement detectors (*P*) of both visual half-fields feed positively into the landing signal integrator ($\int x dt$). The input *x* into the integrator partially habituates (*H*) by repeated stimulation. The input can be sensitized (*S*) by contralateral flicker detectors (*F*). Bilateral rotation detectors perform a multiplicationlike operation (logical AND) between the output of detectors for regressive motion (*R*) in one and of progressive motion (*P*) in the other half of the visual field. They inhibit the output of the landing signal integrator. The graphs symbolize the slow decay of this inhibition. Note that in an equivalent model the regressive pathways instead of the progressive ones cross the midline

that sensitization affects transmitter release by increasing the pool of available presynaptic vesicles.

What could be the behavioural relevance of CoS? It has been shown repeatedly (Eckert and Hamdorf 1983; Wehrhahn et al. 1981; Fischbach 1981; Borst and Bahde 1988; Borst 1990) that bilateral stimuli are very potent in eliciting the landing response, i.e. the response to binocular stimulation is stronger than expected from the sum of the responses to monocular stimuli. Borst and Bahde (1988) argue that this effect is a consequence of the leakiness of the landing signal integrator. During the long latency in response to weak stimuli, leakiness diminishes the integrated signal. Therefore, the response to two simultaneous stimuli is stronger than the sum of the responses to the single stimuli. This mechanism works equally well for intra- and interocular summation, which is one reason why CoS has to be distinguished. No sensitization is observed when a switch between different stimulated fields in the same visual half-field occurs (Fischbach and Bausenwein 1988). An equally strong argument is that leakiness and contralateral sensitization act in totally different time domains (1 s versus 1 min, respectively). Therefore, CoS and leakiness of the integrator are unrelated phenomena. In the normal textured environment of free-flying flies, the long-lasting effects of CoS should lead to a more or less constant level of sensitization. The function of CoS might be a mutual sensitization (or activation) of the optic lobes. Its direction-insensitivity argues in favour of such a more general role.

Can the neurons mediating contralateral sensitization be identified?

So far, all neurons of the lobula plate have been found to be sensitive to the direction of motion in several dipteran species (Hausen 1981). It is therefore unlikely that the lobula plate mediates CoS. Medulla tangential neurons are much better candidates, as no evidence for directional sensitivity at the level of the medulla has been found by the deoxyglucose activity labeling experiments of Buchner et al. (1984) and Bausenwein (1988). Good candidates for the cells mediating contralateral sensitization seem to be the lamina tangential neurons *lat* (Fischbach and Dittrich 1989). These neurons have been shown to bind antibodies against serotonin in *Drosophila* (Buchner et al. 1988) and *Calliphora* (Nässel 1988). The two cell bodies are positioned caudally in the protocerebrum, and their processes bilaterally invade the lamina, medulla and lobula complex (Nässel 1988). It is tempting to speculate that these neurons might mediate contralateral sensitization. Appropriate mutants of *Drosophila* may be helpful in testing the involvement of serotonergic neurons in CoS.

Inhibition of the landing response by bilateral rotation detectors

Stimuli eliciting the turning and landing responses have common components. A single black stripe moving from front to back is an ambiguous signal. It could indicate rotation of the fly which normally would be counteracted by a turning response, or it could imply forward movement of the fly which may lead to speed reduction, or it could be part of a landing stimulus. The fly has to make a decision between the alternate behavioural options.

The ambiguous situation is abolished by adding contralaterally regressive motion. This converts the stimulus to an unambiguous rotatory stimulus, i.e. the landing response has to be suppressed. This inhibition can indeed be observed (Fig. 7). How is it achieved? Is it very telling that the inhibition persists for a while after the regressive component of the rotatory stimulus has been removed. Contralateral regressive motion alone does not elicit such an inhibitory after-effect, it causes contralateral sensitization instead (Fig. 4). Therefore, under our experimental conditions (i.e. stimulation of monocular visual fields only) the inhibition of the landing response is not directly mediated by detectors of regressive motion. Inhibition requires a binocular rotatory stimulus, and the neurons mediating it are detectors of binocular rotation stimuli. This adds another component to our model of the landing response system (Fig. 9). So far, we do not have any information on whether this inhibitory interaction takes place in the optic lobe, the central brain or the thoracic ganglion.

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