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Processing blur of conflicting stimuli during the latency and onset of accommodation

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ABSTRACT

The accommodative response (AR) to changes in dioptric accommodative stimulus (AS) during the latency period and onset of accommodation was investigated. Participants monocularly observed one period of a square wave in AS, with a 2-D baseline and mean, and amplitude 1 D or 2 D; the period of the square wave ranged from 0.10 s to 1.00 s; both increases and decreases were used for the first step in AS. At periods of 0.30 s and longer, accommodation was found to respond to both levels of the stimulus. Rapid retinal monitoring appeared to be taking place for such stimuli. The amplitudes of peaks in AR did not usually depend on whether a particular level of AS occurred first or second, but for 8/40 conditions, a significant difference was found, with a stronger response when the level of AS occurred second. Null or incorrect responses were also observed in many trials, possibly linked with the natural microfluctuations of accommodation. Minimum response times to the changes in AS were observed, which increased with decreasing period of the AS. The time interval between peaks in the AR decreased with decreasing period of the AS. The findings were consistent with a parallel processing model previously proposed for saccades, where input from a later change in stimulus may enter an element of the control system when that element has finished processing an earlier change. More than one change in stimulus may therefore be passing through the multi-element control system at a time.

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1. Introduction

In the 50 years since the work of Campbell and Westheimer (1960), researchers have continued to pursue understanding of the accommodative response (AR) to a dynamic dioptric accommodative stimulus (AS) (Hung & Ciuffreda, 1988; Kasthurirangan & Glasser, 2005; Khosroyani & Hung, 2002; Kruger & Pola, 1986; Phillips, Shirachi, & Stark, 1972; Schor & Bharadwaj, 2006; Stark, Takahashi, & Zames, 1965; Sun & Stark, 1990). They have found and taken into account a latency period of around 370 ms, from a change in AS to the start of the deformation of the crystalline lens. Shao et al. (2013) recently found a latency period of 0.3 s in the response of the ciliary muscle, following a stimulus to accommodate.

Campbell and Westheimer (1960) found that the amplitude of the AR to a brief pulse in AS depended on the duration of the pulse. Even for pulses briefer than the latency period (down to 80 ms), an AR was observed (although it was sometimes absent). They reported that the pulse in AR had a duration very similar to that in AS.

The aim of this experiment was to further probe the AR to changes in AS occurring within the latency. Two conflicting levels of stimulus, and a return to a baseline level, were presented in quick succession. The changes could be performed at 50 ms intervals using the adaptive optics (AO) apparatus. The magnitude and timings of the AR to the various stages of the AS would provide further information about the accommodation control system.

2. Methods

Six participants were recruited from Bradford School of Optometry and Vision Science. Participants were free of ocular pathology; their median age was 25.5 years (range: 21–26 years); further details are shown in Table 1. The experiment was carried out in accordance with the Declaration of Helsinki and ethical regulations at the University of Bradford; all participants gave informed consent to the study.

To achieve the rapid changes in AS required for this study, a deformable mirror (DM) was used (30-mm diameter, 37-channel piezoelectric deformable mirror, Flexible Optical BV, The Netherlands). Reviews of such AO techniques for vision science can be found in Hampson (2008) and Roorda (2011).

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Table 1.
Details of the six participants.

Participant	Gender	Age	Right eye			Left eye		
			DS	DC	x	DS	DC	x
1	F	26	−0.50	−0.25	180	−0.50	0.00	–
2	F	26	−1.00	−0.50	180	−1.25	−0.50	180
3	F	23	+0.50	−0.75	12	+0.50	−0.75	10
4	F	26	+1.25	−1.50	95	+1.25	−1.50	95
5	F	21	−6.25	−0.25	30	−6.25	−0.25	135
6	M	25	−0.50	−0.25	140	−0.50	−0.75	65

This apparatus was a development of the monocular AO system of Hampson, Chin, and Mallen (2009). Lenses L_4 and L_5 (lenses closest to the eye) were replaced with a pair of off-axis parabolic mirrors, to reduce undesired reflections in the system (Edmund Optics, part numbers: NT83-973, NT47-099; diameters: 25.4 mm; focal lengths: 203.2 mm, 101.60 mm).

The target was an image of a black Maltese cross, subtending 10°, on a white background of luminance 5 cd m^{-2}. It was set to a baseline vergence of −2 D at the eye. Following initiation of data collection, there was a 2-s period of baseline target vergence, before the DM effected one period of a square wave in AS. The mean of the square wave in the stimulus was the 2-D baseline; the initial step from the baseline was ±1 D or ±2 D. The period of the square wave was 0.10–1.00 s in steps of 0.10 s. The interval between changes in the stimulus (the interstimulus interval, ISI) was therefore between 0.05 s and 0.50 s in steps of 0.05 s (half the period of the square wave). Examples of the changes in the dioptric stimulus and the AR to them are shown in Fig. 1.

The participants all used their right eye (dominant in all cases), wearing their normal correction. The left eye was occluded. A bite bar, fixed to a translation stage, was used to maintain the position of the participant and for fine adjustment of alignment.

The size cue of a moving target was removed by the Badal arrangement of the eye and the relay optics. A memory cue for the stimulus parameters was removed by randomisation. Static trials and trials with ISI of 2 s were also included amongst the stimuli to avoid a learning effect. Another memory cue, for initial timing, was removed by a random wait of between 1 and 3 s, between informing the participants that the trial had started and initiating data collection. Finally, it was noticed that the DM generated audible clicks when it changed the vergence of the target at the eye. This cue to accommodate was eliminated by masking it with audio input through headphones.

The participant was asked not to blink during each trial. If a participant blinked before 2 s after the dynamic stimulus had returned to baseline, the data was rejected, and a trial with the same settings was inserted into the remainder of the trials to be completed.

For each of the six participants, five trials were carried out at each of the stimulus settings. Therefore, a total of 30 trials were carried out at each stimulus setting.

The infrared wavefront reflected from the eye (Hampson, Chin, & Mallen, 2009) was analysed as a sum of Zernike polynomials (Thibos et al., 2002a), up to 5th order, for each frame captured by the camera. This two-channel AO system allowed aberrometry on the eye without the beam passing via the DM, which simplified analysis. The Zernike coefficients corresponding to defocus and spherical aberration were extracted from the data and converted into accommodation in dioptres (Thibos et al., 2004, 2002b). Changes in this power between the frames revealed the dynamic AR.

The exposure time of the camera was typically 7 ms, which optimised the signal with respect to noise, and the time between frames was between 49 ms and 50 ms. There were 160 frames over the trial, and the first step in target vergence occurred at the 40th frame (2 s from the start of data collection).

Randomisation, data analysis and plotting were carried out using R (R Development Core Team, 2012). Implementation of bootstrap testing followed Rizzo (2008, pp. 197–207). Implementation of Fisher's permutation test followed Rizzo (2008, pp. 217–219).

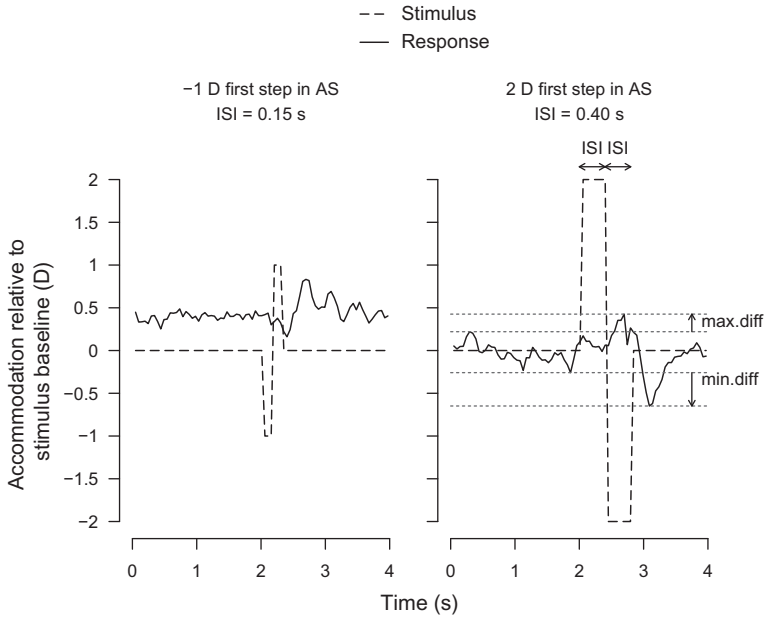

Fig. 1. Examples of the stimulus and time course of the AR during two trials. In the left hand plot, the stimulus initially stepped 1 D further away from the participant, with ISI of 150 ms. In the right hand plot, the stimulus initially stepped 2 D closer to the participant, with ISI of 400 ms. These responses followed both movements of the stimulus, after a latency period. The relative differences of the peaks in AR with the baseline microfluctuations are also illustrated (max.diff and min.diff, used in section 3.1.2).

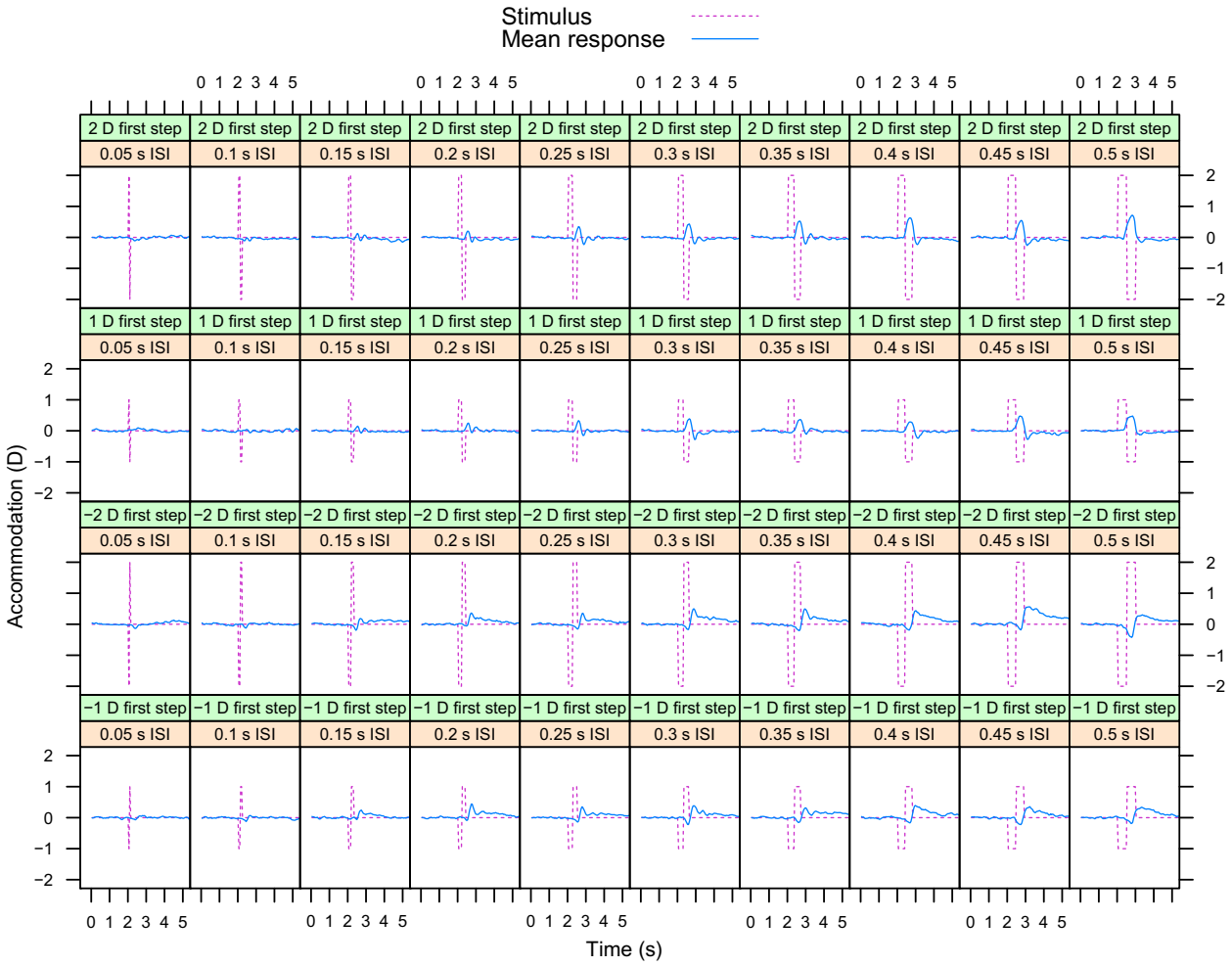

Fig. 2. Mean time courses of the AR to the 40 different stimulus conditions. The stimulus is plotted relative to its baseline of 2 D. The response in each trial was calculated relative to its mean baseline value, before the mean was taken over the trials in each condition.

3. Results and discussion

3.1. The AR to one or both stages of the stimulus

3.1.1. The mean AR

The mean time courses of the AR to the 40 stimulus conditions are shown in Fig. 2. A mean response can be seen, following the stimulus, even down to some of the briefest stimuli.

3.1.2. Statistically significant peaks

To judge whether peaks in AR were statistically significant, maximum and minimum values of the AR were extracted for each trial. These were taken from the data beginning at the first change in AS and ending 1 s after the return to baseline, following the two stages of the dynamic AS. Evidence in Campbell and Westheimer (1960) shows that the AR to a brief pulse in AS reaches its peak in well under 1 s of the return to baseline, so this limit was considered sufficient.

For each trial, the maximum and minimum AR were calculated relative to the mean level of the fluctuations of accommodation in the 2-s baseline period. Their difference from the maximum and minimum of the fluctuations in the 2-s baseline period was also calculated (giving max.diff and min.diff for each trial, as in Fig. 1).

Data for the peaks in AR at each trial condition indicated rough approximations to normality. However, many of the samples failed the Shapiro–Wilk test ($p < 0.1$). Therefore, non-parametric analyses were applied. The median was used for comparisons of central tendencies among the data.

If, for one trial condition, the thirty trials showed that the median of max.diff > 0, or the median of min.diff < 0, with 95% confidence, it was concluded that there was a significant AR in the relevant direction(s). A null result would indicate that the AR may have simply been a continuation of the baseline fluctuations. One-tailed 95% confidence intervals for the medians of max.diff and min.diff in each case were found using bootstrap resampling (BC_a bootstrap confidence interval (Efron, 1987), using 10,000 replications).

The median peaks in AR, with respect to the average baseline value are plotted in Fig. 3. 95% confidence of a significant peak in AR is shown by an open square. A statistically significant response in at least one direction (any open square) was identified at ISIs from 0.05 s to 0.50 s. Significant responses were identified in both directions at 21 of the 40 stimulus conditions, at ISIs ranging from 0.15 s to 0.50 s (a pair of open squares for maximum and minimum AR at any condition in Fig. 3).

3.1.3. Categorisation of the AR in individual trials, by number and direction of peaks outside the baseline fluctuations

The number of peaks in AR beyond the baseline extrema was also found for each trial. The trials were categorised as illustrated in Fig. 4. Fig. 5 shows the relative contributions of the various categories of response.

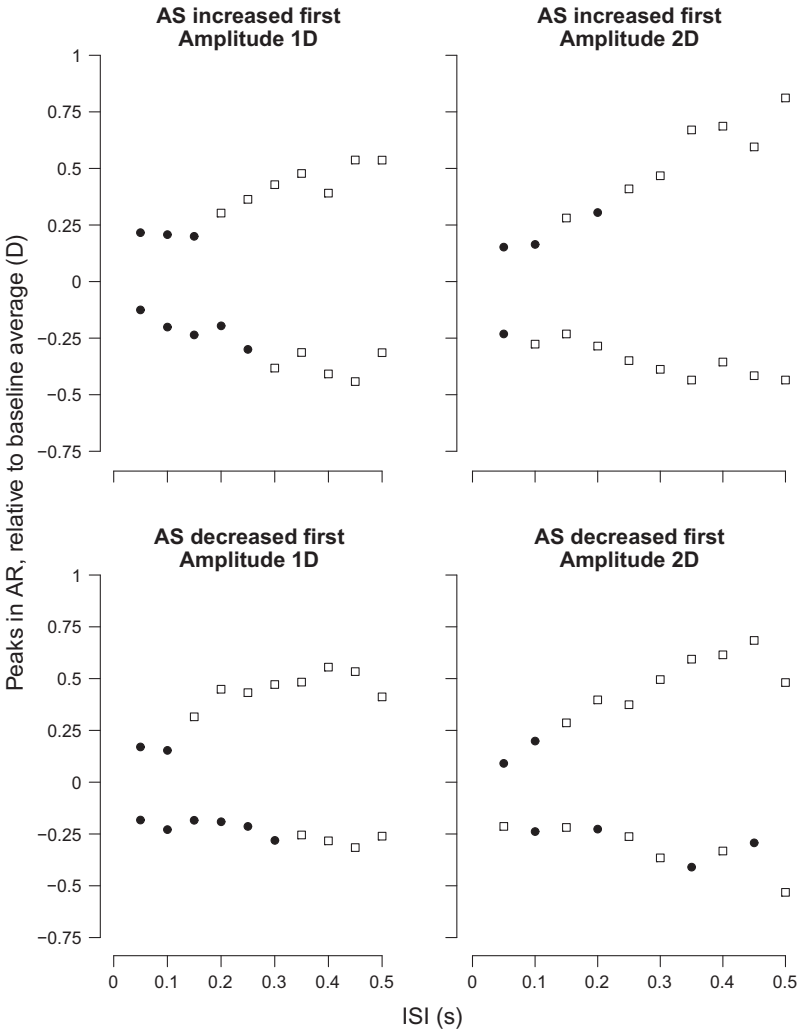

Fig. 3. The median maxima and minima of accommodation in all trials. An open square indicates that the median peak in AR following the stimulus was found to be significantly outside the extremes of the baseline fluctuations of accommodation ($p < 0.05$, using bootstrap confidence intervals; see text).

In 14 of the 40 trial conditions, there were at least as many trials with a double response in the expected order as there were with all other types of response combined. All but one of these 14 conditions resulted in statistically significant peaks in AR to both stages of the stimulus (see Section 3.1.2). Double responses with inverted order (“incorrect double responses”) will be briefly discussed later (Section 4.3).

3.1.4. Amplitudes of double and single responses

For the 21 conditions in which there were statistically significant responses in both directions (Fig. 3), the double responses with the expected order (“correct double responses”) were tested against the EARLY and LATE single responses (see Fig. 4). Fisher’s permutation test was used; a significant result would indicate that the peaks of correct double responses were not part of the same population as the EARLY or LATE single responses, as identified by a smaller median peak amplitude for the double responses.

In 10 out of the 21 conditions, one or both of the peaks of the double responses were significantly smaller than the corresponding single responses (Fisher’s permutation test on the difference of the medians, 9999 replications, using $p < 0.1$). In the other eleven conditions, neither peak of the double response was found to be significantly smaller than the corresponding single response ($p > 0.1$). In total, 12 of the 42 peaks (2 peaks $\times$ 21 trial conditions) revealed a significant result. 1/4 of the peaks tested at ISI 0.15 s revealed a significantly smaller response than the corresponding single response. 1/4 was the median proportion of peaks yielding significant results at the different values of ISI (0.15 s and 0.25–0.50 s).

3.2. Effect of whether a given level of AS occurs EARLY or LATE

Among single responses, there were 278 EARLY responses and 295 LATE responses. These are consistent with equally likelihood for single EARLY and single LATE responses. In a binomial test for a difference in likelihoods, no significant difference was found ($p = 0.50$).

The correct double responses were also tested for a difference in the AR to a level of AS occurring as either the EARLY or LATE stage in a trial. The EARLY maxima in AR (when the maxima in AS occurred first) were compared with the LATE maxima in AR (when the maxima in AS occurred second, i.e. when the two stages of the AS were reversed). Minima in AR were compared similarly.

Table 2 shows which position (EARLY or LATE) of the level of AS within a trial elicited a stronger peak in AR, when there was a significant difference between them. Fisher’s permutation test on the difference of the medians was used, with 9999 resampling permutations and a significance threshold of $p < 0.05$. A significant result

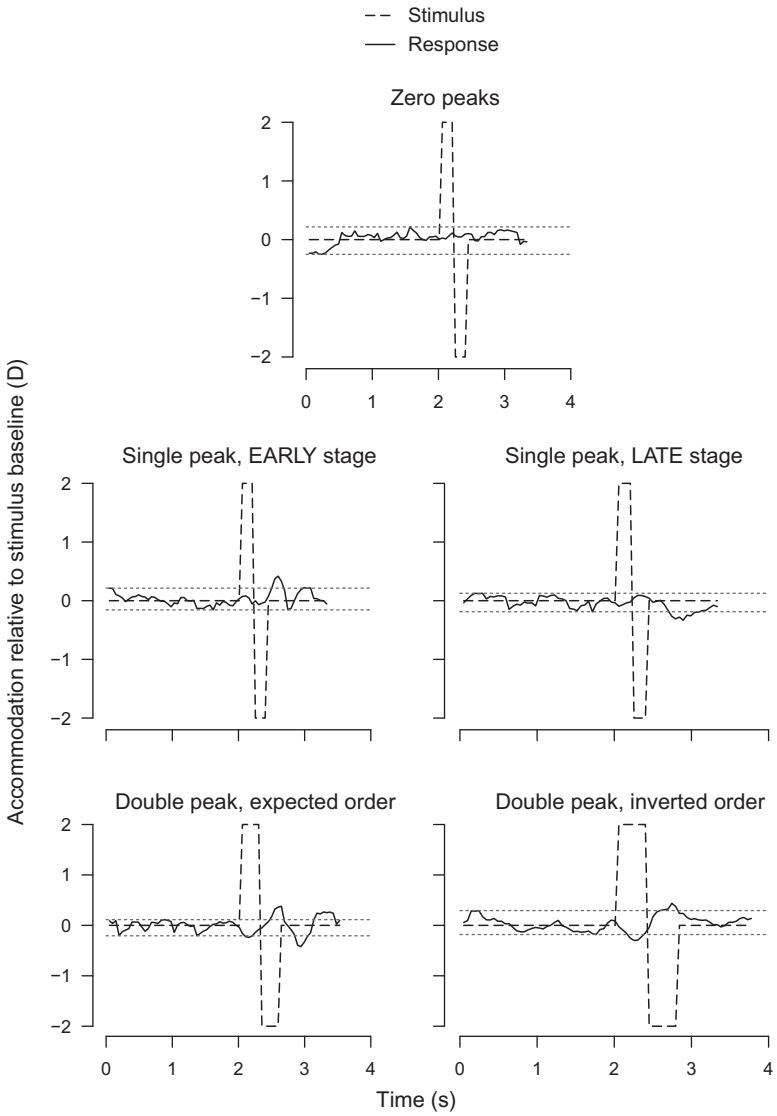

Fig. 4. Examples of the categories of response, by number of peaks beyond the baseline fluctuations. The extrema of the baseline fluctuations are shown with short dashed lines. The single responses are further categorised according to whether the single peak is in the direction of the EARLY or LATE stage of the AS. The double responses are further categorised according to whether the maximum and minimum are in the same order or inverted, with respect to the order of the levels of the AS.

indicates that the EARLY and LATE peak responses were found not to be part of the same single distribution of peak responses, as identified by the difference of the medians.

Before taking into account multiple comparisons, there were eight combinations of the level of AS and ISI at which the AR to the LATE stage AS was significantly different from ($p < 0.05$), and stronger than, that to the EARLY stage AS. This difference was found for both levels of the trials with amplitude 1 D and ISI 0.40 s. A further three stimulus levels and intervals approached a significant difference ($p < 0.1$); all had a greater median for the response to the LATE stage AS than the EARLY stage AS.

There was a small, but statistically significant, degree of correlation between the maxima and minima in each trial (Kendall's $\tau = 0.10$, $N = 1200$, $p < 0.01$). Therefore, they may have been partially dependent on each other. The two results at amplitude 1 D and ISI 0.40 s may be considered not truly independent. There are therefore 7 truly independent findings as described above, and we may also consider 20 of the 40 possible tests to be independent.

The likelihood of finding these significant differences by chance is therefore between that of at least 7 out of 20 independent findings and that of at least 8 out of 40, at $p < 0.05$, by chance, i.e. between 0.00004 and 0.0007. Therefore it is likely that a real difference between the LATE and EARLY stages of the double response has been found.

The single result where the response to the EARLY stage AS was greater (+2 D, 0.50 s) is not significant after similar correction for multiple comparisons ($p > 0.5$, using either the original significance threshold of 0.05 for P(type I error), or the exact probability of 0.027 in that case).

3.3. Timings of the AR

The response times of the different stages of the AR were also considered. Similarity of the small ARs with the baseline fluctuations made it difficult to examine the timing of the response to the first change in AS. However, the timings of the two peaks in a correct double response provided the two response times (RT2, RT3, Fig. 6) and the inter-response interval (IRI, Fig. 6). Attempts

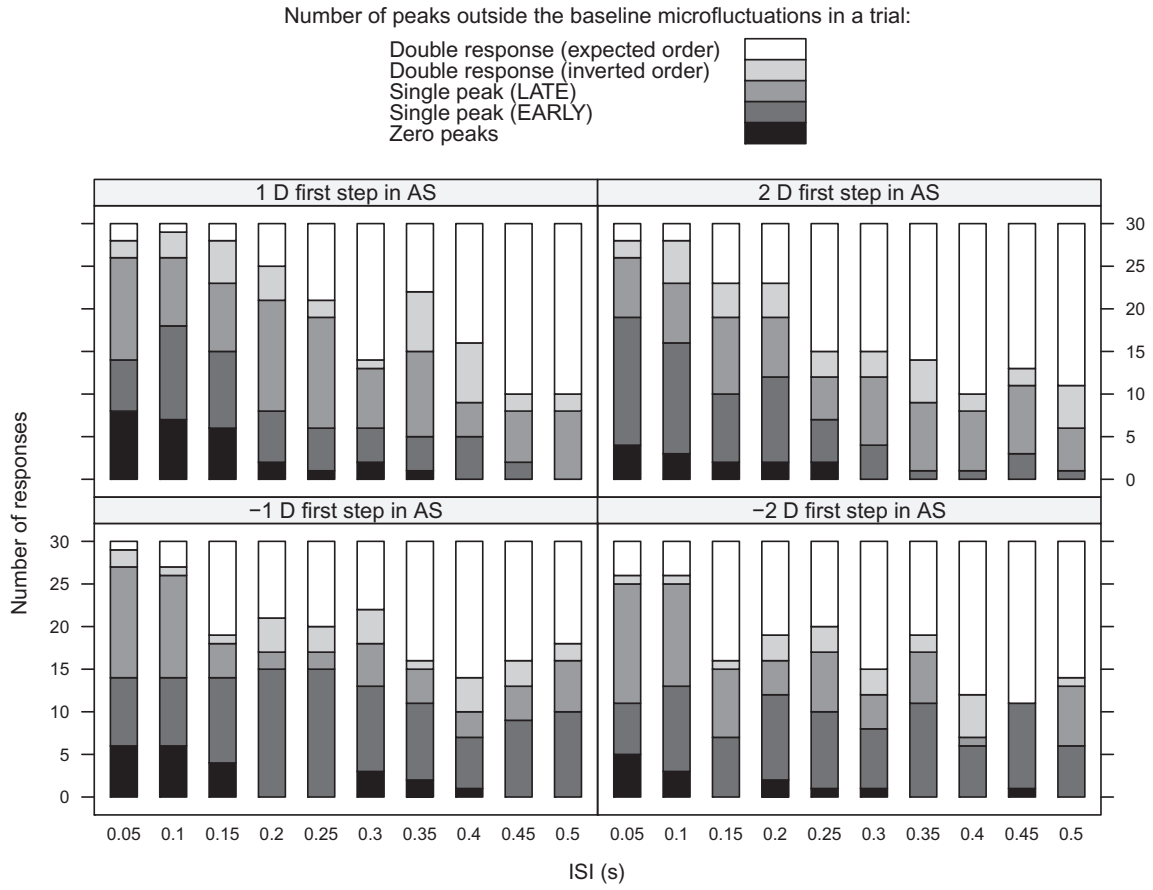

Fig. 5. The numbers of trials with different numbers and orders of peaks in AR outside the baseline fluctuations. The legend is further explained in Fig. 4. The relative proportions of the different types of response can be seen in the stacked bars.

Table 2.
Tests for significant differences between peak responses to the levels of the AS, depending on whether that level of the AS was the first or second stage of the square wave. Only trials with a double response in the expected order were considered. "-" indicates there were fewer than five such trials for at least one of the trial conditions in each comparison. "ns" indicates no significant difference. "**LATE**" and "**EARLY**" indicate a significant difference ($p < 0.05$) and in which stage of the stimulus the stronger median response was found. "(LATE)" indicates a difference approaching significance ($p < 0.1$). See text for details of the statistical test.

Stimulus interval (s)	Level of AS, relative to baseline			
	−2 D	−1 D	+1 D	+2 D
0.05	–	–	–	–
0.10	–	–	–	–
0.15	ns	–	–	ns
0.20	**LATE**	ns	ns	ns
0.25	**LATE**	**LATE**	ns	(LATE)
0.30	ns	ns	ns	ns
0.35	**LATE**	**LATE**	ns	ns
0.40	ns	**LATE**	**LATE**	(LATE)
0.45	(LATE)	ns	ns	ns
0.50	ns	**LATE**	ns	**EARLY**

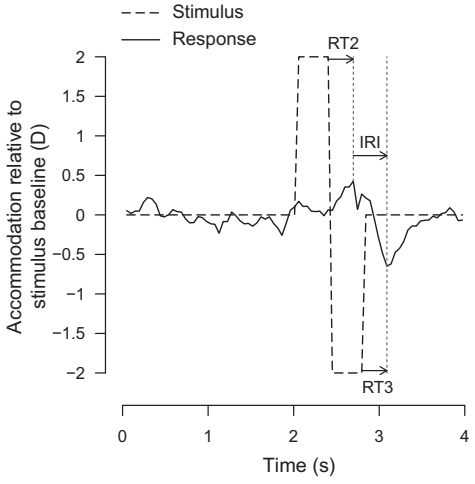

Fig. 6. Definition of the second and third response times (RT2 and RT3) and inter-response interval (IRI) for a double response (expected order). The response times are defined to the peaks in AR caused by the second and third changes in stimulus. In general, a response time to the first change in AS was difficult to define due to similarity of that part of the AR to the microfluctuations.

to use velocity or acceleration of AR for analysis were less meaningful, owing to artefacts introduced by smoothing of the data to avoid the noise of the natural fluctuations.

Fig. 7 describes the IRI for correct double responses in each stimulus condition. The conditions where AS decreased first resulted in much more varied results, and in general, longer IRI. When AS increased first, there appeared to be trends where IRI decreased with decreasing ISI. These trends broke down at brief ISIs, where there were a low number of double responses. At brief ISIs,

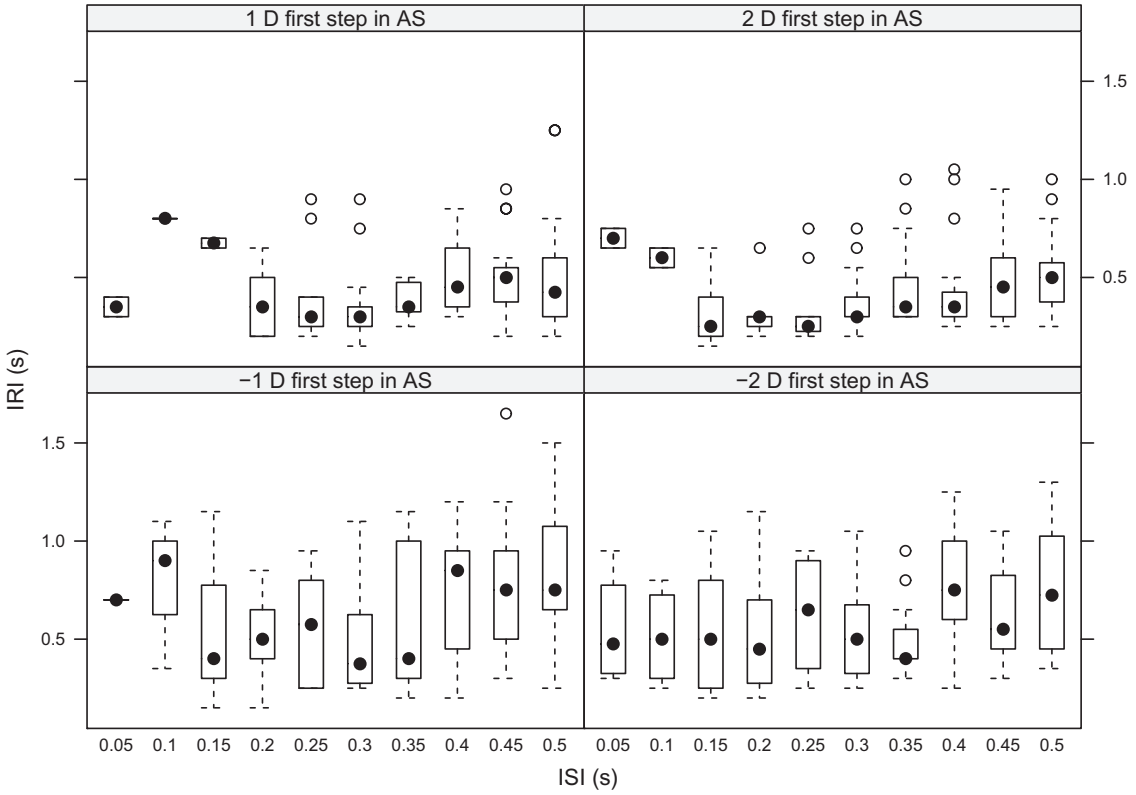

Fig. 7. Box plots describing the IRI in trials with double responses (expected order).

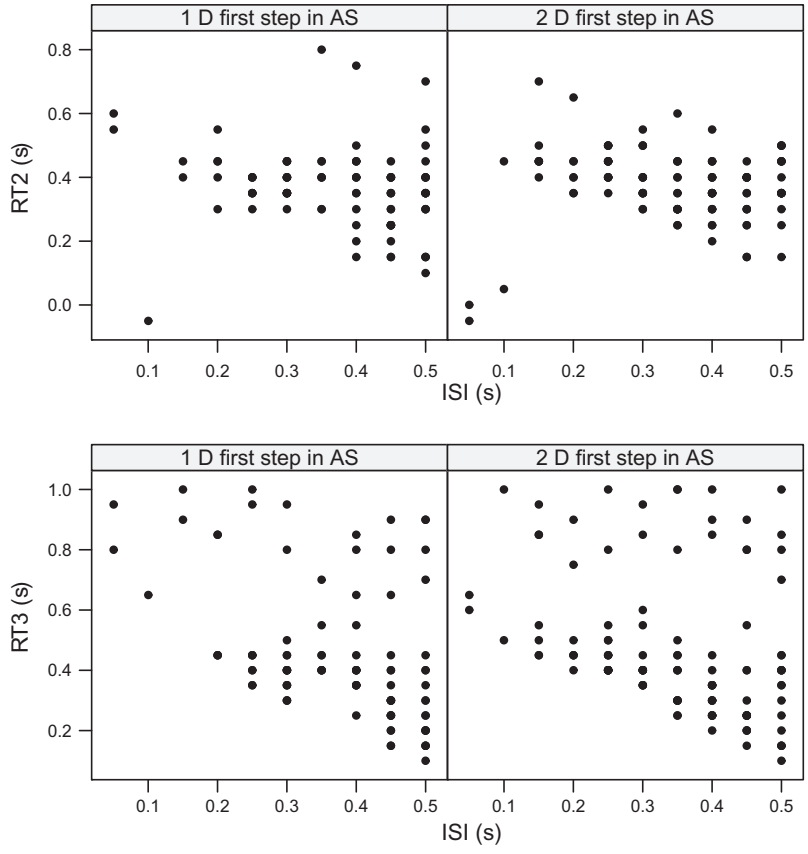

Fig. 8. Scatterplots showing RT2 and RT3 against ISI, for trials in which the first step in AS was an increase, and which resulted in a double response (expected order). (The measurements have a time-resolution of 50 ms; several trials share the same RT2 or RT3 in many cases.).

the fewer double responses, with smaller peak amplitudes, were more likely to be fluctuations of accommodation when it had insufficient information for a controlled double response.

The most conditions with a statistically significant response to both stages of the AS were found when AS increased first, by a step of 2 D (top-right of Fig. 3). These conditions also showed the clearest trend for IRI (top-right of Fig. 7). A linear regression of the medians of these data, at ISI from 0.25 s to 0.5 s, found that

$$\mathrm{IRI} = (0.95 \pm 0.11) \times \mathrm{ISI} + 0.00 \pm 0.04,$$

where the confidence intervals are one standard error ($R^2 = 0.94$). This is consistent with IRI = ISI, although including intervals of 0.20 s and 0.15 s resulted in models not consistent with this relationship. The double responses were not statistically significant for ISI briefer than 0.15 s (Fig. 3).

Scatter plots of RT2 and RT3 may also be examined, as in Fig. 8. Here, minimum response times are apparent which increase with decreasing ISI. The very short response times for longer ISI may be attributable to the predictable general pattern of the stimulus, similar to the short latencies observed by Phillips, Shirachi, and Stark (1972). However, the variation of IRI with ISI shows that there was not a single learned response; the extra stimuli included among the trials, which were static or had ISI of 2 s, also mitigated against this. Negative response times reveal the inclusion of some random fluctuations in the peaks of individual "double responses". This was expected, hence the analysis of Section 3.1.2. A greater number of negative RT2s were found for stimuli with AS decreasing first (not shown).

Excluding the outliers in RT2 at ISI $\leqslant$ 0.1 s, Fig. 8 demonstrates minimum response times which increase with decreasing ISI. Excluding the same outliers, (RT2 + ISI) had a minimum of either 0.55 s or 0.60 s in all conditions but three (one with 0.50 s and two with 0.65 s).

(RT3 + ISI) had a minimum of 0.60 s or 0.65 s in all conditions but four (all with a 1-D first step; these are apparent in the lower left of Fig. 8).

4. Discussion

4.1. The double-AR; continuous monitoring and parallel processing

The findings of Campbell and Westheimer (1960) suggested continuous monitoring by the accommodation system. However, when the duration of the single pulse in AS was 100 ms or shorter, or the pulse was a diminution of the dioptric stimulus, some responses were absent. This may have indicated, first, minimum processing times for an AR, e.g. to trigger sampling of the AS and the sampling time itself. Second, decreases in AS may not be as strong a cue to accommodate as are increases.

In the current study, it was possible to present rapid changes between three levels of dioptric stimulus (including the baseline) and record the AR. Section 3.1 reported the statistical responses in both directions from the baseline, the prevalence of correct double responses in individual trials and the comparable strength of correct double responses and single responses. These results indicate that accommodation responded in both directions to such a succession of conflicting stimuli, at least down to an ISI of 0.15 s.

At ISI of 0.15 s, and amplitude 2 D, both stages of the stimulus were completed within the usual latency of accommodation, and still elicited the AR in both directions. This result, in particular, supports the theory of continuous monitoring of the AS during processing of previous input, including stimuli more complex than a single pulse. By the time of the EARLY stage of the response, even the LATE stage of the stimulus was in the past, yet the LATE stage of the AR was still effected. The sampling of AS for the LATE response was carried out during the latency (preparation time) of the EARLY response. EARLY and LATE responses were therefore being prepared concurrently, likely at different stages of the preparation process, as proposed for the saccadic response to double-step stimuli (Becker & Jurgens, 1979).

Further, the LATE response appears to have taken the EARLY response into account, in producing a significant peak beyond the baseline. (See also Section 4.4 on relative strengths of the peaks in AR.)

One reason for the observed limit of double responses at ISI = 0.15 s may be that the AR becomes indistinguishable from the fluctuations of accommodation using these methods. Another may be that this is close to a minimum time window for the sampling of retinal blur, once such sampling has been triggered. Similarly, Campbell and Westheimer (1960) found that responses were sometimes absent at single pulse durations of 100 ms or shorter.

From Fig. 3, there were fewer conditions with a statistically significant double response when the AS had amplitude 1 D, than at 2 D, and fewer when AS decreased first than when it increased first. The changes with amplitude 2 D thus provided clearer cues for the continuous monitoring than those at 1 D, and the same appears to be true for increases in dioptric stimulus, as opposed to decreases. The smaller decreases in AS when AS decreased first, as opposed to second, appeared to result in fewer ARs. This difference between increases and decreases in dioptric stimulus was also found by Campbell and Westheimer (1960).

4.2. Single responses and time-variance of the accommodation system

There also appeared to be responses to only a single stage of the stimulus. Both EARLY and LATE stages of stimuli elicited single responses, with the other stage of the response apparently absent. Single responses were observed at all ISIs down to 0.05 s. In nearly half of the conditions considered in Section 3.1.4, single responses were significantly stronger than at least one stage of the double response. There were also null responses, which did not exceed the baseline extrema. Single responses were equally likely to be to the EARLY or LATE stage of the AS.

There therefore appears to be a varying property in the accommodation system that causes identical changes in AS to result in different, or null, ARs. A link with the natural fluctuations of accommodation (observable in Figs. 1 and 4) is a candidate for further investigation.

4.3. Incorrect double responses

The AR in some trials contained both maximum and minimum outside the range of the baseline fluctuations, but in opposite order to the levels presented in the AS (Figs. 4 and 5). The mean peaks in AR of incorrect double responses were comparable in amplitude to those of correct double responses.

In these responses, a decision has first been made to respond in the wrong direction, with respect to the stimulus. In the absence of many normal cues (size, disparity, relation with surroundings) this phenomenon has been observed before, particularly for steps of decreasing AS (Chin, Hampson, & Mallen, 2009). Secondly, however, either the direction error persists in the second stage of the AR, or the accommodation system has realised the error and attempted to respond belatedly (the AS has returned to baseline by this time.) The processing of these apparent, incorrect, double decisions also warrants further study.

4.4. Comparison of EARLY and LATE peaks in AR

In Section 3.2, it was found, in correct double responses, that there was usually no significant difference between the AR to a

given level of AS occurring either EARLY or LATE in a trial. When there was, the AR to the level of AS occurring LATE was likely to be greater than the AR to the same level of AS occurring EARLY (true for 8/40 conditions). In general, the LATE peak was not attenuated by the EARLY stimulus and response, at least not any more than the EARLY response was attenuated by the LATE stimulus and response.

In order for the LATE response to not be significantly weaker than the EARLY response, the accommodation controller must use information both about what the accommodative state will be, or is, at the time of onset of the LATE response, and where the response should aim for. i.e., the step was deliberately made to start from the current, or estimated state, and was not relative to the baseline. If the LATE response was based solely on the defocus information from the LATE stage of the AS, the defocus errors for the EARLY and LATE responses would be equal and opposite. In that case, we would expect the responses to be roughly equal and opposite, and the LATE result would return accommodation approximately to the baseline level. In particular, when AS increased first, we would not expect the weaker response to the LATE decrease in AS to result in a peak beyond the baseline. Analogous "extra-retinal" error processing has been found in the saccadic system (Becker & Jurgens, 1979). The predictive capacities of accommodation offer another example (Phillips, Shirachi, & Stark, 1972).

There are a few possible explanations for a tendency for the LATE peak AR to be stronger than the EARLY. One is that information from different periods during the latency interval and onset of accommodation is weighted with different priority. Conflicting information from later in the latency may be allowed higher importance because it is temporally closer to the actual AR.

A related explanation is that the accommodation controller may be triggered to integrate AS over a time window that can extend beyond a subsequent change in AS. In that case, inclusion of part of the LATE stage of the AS in the integration for the EARLY response could attenuate the EARLY response more than the inclusion of the final baseline AS in the integration for the LATE response would attenuate the LATE response.

Finally, the larger change in AS for the LATE response may have resulted in an increased velocity. Accommodation may have therefore progressed further beyond the baseline before it was checked by the final signal to return to baseline. It is already known that the magnitude of a step-change in accommodation affects velocity and acceleration (Kasthurirangan & Glasser, 2005; Schor & Bharadwaj, 2006).

4.5. Timing

It was found in Section 3.3 that for the strongest cues, eliciting the most double responses (2 D initial increase in AS) a clear trend was observed, where the IRI decreased with decreasing ISI. For longer ISI, the findings were consistent with IRI = ISI, and there may be a lower limit at 0.25 s for this relationship.

Also, the individual response times for the peaks in AR (RT2 and RT3) had minimum durations which increased with decreasing ISI, such that (RT2 + ISI) and (RT3 + ISI) appeared to have a consistent minimum of around 0.55–0.65 s, independent of ISI. No exact data for such short pulses has been found in Campbell and Westheimer (1960) or elsewhere for comparison.

These data are consistent with the existence of a minimum time interval for two changes in AS and two responses of accommodation. The preparation time of the second response may be limited by the concurrent preparation of the first response, as expected in the parallel processing model discussed in Section 4.1.

To produce a consistent EARLY response when ISI = 0.15 s, the time window for sampling AS must be either shorter than about 0.15 s, or cut short by the second change in AS, as in the model of Khosroyani and Hung (2002). That model successfully accounted for both the pulsed and step responses of Campbell and Westheimer (1960) and the complex ramp responses of Hung and Ciuffreda (1988).

4.6. Limitations of the experiment

There was a risk that accommodation may be delayed in this protocol, and that peaks in accommodation could be missed in analysis by using the cut-off point of 1 s after the last change in stimulus (see Section 3.1). On the other hand, fatigue-related drifts in accommodation and blinks were more likely to be included by relaxing the cut-off. It may be possible to design a better algorithm for searching for relevant peaks in the AR; more significant responses may be found in that case.

Frames were captured every 50 ms, and each provided an analysis of the average wavefront over the 7-ms exposure time. Measurements every 50 ms should be sufficient to capture peaks in AR, but greater time-resolution would provide more accurate results.

Velocity and acceleration information would have allowed further analysis of latencies and the role of feedback during the AR (Bharadwaj & Schor, 2005). Unfortunately, the microfluctuations of accommodation confounded attempts to extract this information, as explained in Section 3.3.

5. Conclusions

A square wave in dioptric stimulus was observed by the six participants, under monocular conditions. By analysing the AR, it was found firstly that sampling of the retinal input appears to take place over the course of the latency and onset of accommodation. The results of the sampling are carried over into a double response, even when the two stages of the dynamic stimulus are completed within the latency of accommodation. There appeared to be a significant double response for dynamic stimuli with ISI down to 0.15 s. The accommodation controller may respond in a similar way below this limit, but with the AR obscured by the microfluctuations of accommodation.

The two stages of a double response were most likely not to be significantly different from each other, but 8/40 of the stimulus conditions resulted in a stronger LATE peak than the EARLY peak. This may indicate a favouring of later information over earlier, for short ISI, either via a weighting function for defocus information over time or by integration over a certain time window. Alternatively, the effect may be due to the application of a high velocity of accommodation in response to the larger second step, to the extent that the second response is more extreme than the first, by the time the return to baseline takes effect.

The presence of single responses (equally likely to be EARLY or LATE) and null responses at various stimulus intervals indicates a time-variant starting condition for the accommodation control process. It is speculated that this may be linked to the microfluctuations of accommodation. Possibly also connected, incorrect decisions were sometimes taken as to the direction of response to two changes in AS in quick succession.

IRI decreased with decreasing ISI, and was approximately equal to it for the strongest stimuli. Response times to the second and third changes in AS (timings of the peaks in AR) increased as ISI decreased. This indicated, together with the double response at brief ISI, that the preparation for a later change in accommodation could begin during the preparation period for a prior change. The later change may be allowed to be processed in the ith stage of the preparation process when the earlier change has moved on the $(i+1)$th stage. The IRI

would then be limited by the longest stage of the preparation process, and the response time by the total preparation time for an AR (including predictive effects). The response time would increase as ISI decreased, as the processing of the later AR had to wait at different stages for the processing of the earlier AR to pass through the system.

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