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## RESEARCH ARTICLE

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## Timing a one-handed catch

### II. Adaptation to telestereoscopic viewing

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**Abstract** A pre-exposure, exposure, post-exposure design was used to assess the adaptation of the timing of a one-handed catch during telestereoscopic viewing. More specifically, it was examined whether the adaptation involved: (1) ignoring binocular sources of information and selecting other information, or (2) a recalibration of the coupling between the effected binocular information and the catching movement, and (3), if it is recalibration, whether it is restricted to the manipulated binocular information. To test these hypotheses, subjects ( $n=16$ ) were assigned to one of two groups, each group performing three blocks of 15 trials in the dark with only the ball visible. In the exposure condition, both groups were required to catch balls under binocular telestereoscopic viewing. In the pre-exposure and post-exposure conditions, subjects performed under binocular and monocular viewing, respectively. Kinematics of the grasping movement were recorded. It was predicted that, in the case of a selection process, no aftereffects would occur in the post-exposure condition, whereas, in the case of recalibration, aftereffects would occur. Moreover, if the recalibration is restricted to the manipulated information, only the group that was provided with binocular vision during the pre-exposure and post-exposure conditions would show aftereffects. Significant condition (pre-exposure, exposure, post-exposure) by block (first three trials, last three trials) effects were found for the moments of grasp onset, peak opening velocity and hand closure, indicating that the hand was opened and closed earlier in the first three trials of telestereoscopic viewing. This coincided with an in-

crease in catching failures. In addition, for the moments of hand closure and peak closing velocity, negative aftereffects were found in the post-exposure condition. The hand was closed later in the first three trials after removal of telestereoscope. With respect to the presence of the aftereffects, no differences were found between the groups. It was concluded that adaptation to telestereoscopic viewing in the timing of a one-handed catch is due to the recalibration of the coupling between information and movement, rather than a selection of another source of information. Moreover, it is likely that the recalibration was not restricted to the single, manipulated information. Rather, the recalibration involves multiple binocular and monocular optical and oculomotor sources of information.

**Key words** Adaptation · Selection · Re-calibration · Timing · One-handed catching · Binocular information

### Introduction

Information, detected by various perceptual systems, tunes an action system to its environment. Proponents of an ecological approach to perception and action (Gibson 1979; Turvey 1990) hold that information is specific to events and actions. Understanding the control of movement, therefore, requires the identification of the information. An outstanding example of this approach is the research on the timing of interceptive actions, such as catching, hitting and punching a falling ball. Achieving accurate timing of such actions requires information on the time remaining before an approaching object reaches the interception point. Lee (1976) has demonstrated that such information is specified by the relative rate of dilation of the closed optical contour, denoted tau, generated by the approaching object. Inventive experimentation (e.g. Lee et al. 1983; Savelsbergh et al. 1991, 1993) had convinced many that tau exclusively regulates the temporal aspects of interceptive actions.

Nevertheless, recent theoretical considerations suggest that multiple sources of information may contribute

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to the specification of time-to-contact (e.g. Heuer 1993; Laurent et al. 1996; Regan 1997; Tresilian 1990). Subjects have been found to demonstrate a remarkable flexibility in successfully adapting their movements to changes in task constraints and, hence, the available information. Kinematic analyses have revealed that the (differences between) timing patterns are not always consistent with an exclusive guidance by tau (e.g. Bennett et al. 1999; Scott et al 1997; Van der Kamp et al 1997; Wann and Rushton 1995). It often remains unsolved, however, whether the observed adaptation to the changing task requirements is based on a recalibration or "retuning" of the existing information-movement coupling or whether the original information is ignored and other information is selected (cf. Cutting 1986, 1991; Laurent et al. 1996; Reed 1996).

In the accompanying paper by Bennett et al. (1999), for instance, it was demonstrated that telestereoscopic viewing resulted in a decrement in one-handed catching performance (cf. Judge and Bradford 1988). The telestereoscope consists of an arrangement of mirrors whereby the interocular separation is increased. On the one hand, telestereoscopic viewing enlarges binocular disparity, convergence and presumably effects accommodation (Fisher and Ebenholtz 1986). Thus, objects are perceived at a shorter distance than their actual distance. On the other hand, monocular sources of information (e.g. optical expansion, tau), and binocular tau-function variables (i.e. an optical variable divided by its rate of change) remain unaffected. Bennett et al. (1999) showed that wearing the telestereoscope clearly affected the timing pattern of the one-handed catch; the hand was closed earlier when wearing the telestereoscope under binocular viewing. Consequently, this finding rules out the suggestion that the temporal characteristics of the grasping movement were exclusively controlled by either monocular or binocular tau-like sources of information. Bennett et al. (1999) noticed that subjects quickly adapted to telestereoscopic vision such that, within a few attempts, subjects had changed their timing pattern and the remaining balls were caught successfully. Did subjects recalibrate the existing information-movement coupling or was, after ignoring or neglecting the misleading binocular information sources, another (e.g. monocular) information source selected?

This issue will be examined by using a pre-exposure, exposure, post-exposure design, similar to that often used in research on adaptation to rearranged vision, such as prisms (e.g. Jakobson and Goodale 1989; Welch 1974). Usually pre- and post-exposure conditions are compared, and recalibration is attested for whenever a negative aftereffect is found. Jakobson and Goodale (1989), for instance, showed that, when subjects reached to prismatically displaced targets, they adjusted by increasing the curvature of their reaches. According to the authors, recalibration occurred as attested for by a negative aftereffect, that is, a systematic directional bias opposite to the one introduced by the prisms following the exposure to prisms.

Wallach et al. (1963) were the first to explore the nature of the adaptation process using a telestereoscope in a pre-exposure, exposure, post-exposure procedure. Subjects were required to estimate the depth of a wire-form object by adjusting the length of a metal rod to equal its apparent depth. After a 10-min exposure period, in which observers passively viewed the rotating wire-form object through the telestereoscope, aftereffects were obtained in judging the depth of the object. That is, when looking directly at the wire-form after the exposure period, the apparent depth of the wire-form was significantly decreased. This finding was replicated by Epstein (1968). Both authors argued that binocular disparity was recalibrated by monocular kinetic depth information (i.e. generated by the rotated object). This conclusion was contested by Fisher and Ebenholtz (1986), who found, in the case of two-dimensional targets, aftereffects following telestereoscopic exposure could be obtained when either disparity or kinetic depth information was absent during the exposure interval. They suggested that the aftereffects were mediated by oculomotor information (i.e. accommodation). Whatever the precise information involved, the common opinion on the observed aftereffects in the perceptual judgement studies is that they occur due to some type of recalibration. However, with respect to the information-based regulation of action, there are important limitations with these perceptual judgement studies due to the use of stationary objects (i.e. there is no motion in depth) and the fact that perceptual error has no consequences. In contrast, when intercepting approaching objects, the increase in interocular separation leads to a deterioration in catching performance (Bennett et al. 1999), resulting in a much higher pressure to adapt to the new circumstances than in the case of perceptual judgements. Therefore, it is still an open question whether other information is selected or whether the existing information-movement coupling is recalibrated in interceptive timing acts during telestereoscopic viewing.

In the present experiment, therefore, subjects were required to catch balls moving on a spatially fixed path, first under normal vision (i.e. pre-exposure), then during telestereoscopic vision (exposure) and finally again under normal vision (post-exposure). It was predicted that, in the first few trials under telestereoscopic viewing, the hand would be closed earlier, or even too early, resulting in catching failures (cf. Bennett et al. 1999; Judge and Bradford 1988). Subsequently, subjects should quickly adapt and start closing their hand later, enabling them to again successfully catch the balls. If the process of adaptation involves a recalibration of the coupling between the binocular information and the catching pattern, then the hand would be predicted to be closed later, or even too late, in the post-exposure condition. In contrast, if this negative aftereffect was not observed, that is, if there was no difference between the timing pattern exhibited in the final pre-exposure, the final exposure and the first post-exposure trials, then the implication is that the orig-

inal binocular information source was ignored and another source of information was selected to guide the catch.

The second manipulation in the present study involved a between-subject design, in which viewing in both the pre-exposure and post-exposure trials was either monocular or binocular, while telestereoscopic viewing was always binocular. Savelsbergh and Whiting (1992) showed that relatively poor catchers, who improved their catching performance (i.e. a decrement in the number of spatial errors) during monocular practice sessions, kept performing at a same level when transferred to binocular viewing, indicating a continued guidance by monocular information. Hence, in the case of monocular pre-exposure, subjects could already be regulating their catch by monocular sources of information. This may reduce the need for selecting binocular information sources, which subsequently need to be recalibrated to the movement.

Recently, several authors have argued that multiple sources of information contribute to the specification of time-to-contact, albeit primarily in the context of prediction-motion tasks, (e.g. Heuer 1993; Tresilian 1994; but see Wann and Rushton 1995). Hence, various binocular and monocular optical sources of information, as well as oculomotor information such as changing vergence and accommodation, have been suggested to be simultaneously involved in the regulation of the temporal kinematics of interceptive actions. In contrast, others have assumed that temporal control is limited to a single source of information (e.g. Laurent et al. 1996; Lee et al. 1983; Savelsbergh et al. 1991; Servos and Goodale 1998; Van der Kamp et al. 1997), which may differ depending on the task constraints. This raises the issue whether, in the case of an adaptive recalibration of information to movement, the recalibration is restricted to the affected information source only or whether multiple sources of information are recalibrated. In the previous studies on adaptation to telestereoscopic viewing, the observed recalibration was regarded as being restricted to binocular information (Epstein 1968; Judge and Bradford 1988; Wallach et al. 1963). For instance, Judge and Bradford's (1988) finding of no aftereffects in a monocular condition after adapting to binocular telestereoscopic suggested that learning was restricted to binocular information. However, the recalibration of binocular information by the unaffected monocular sources of information may result in an adaptive change of other information as well.

This forms the second motive for using the between-subject design, where, for one group, viewing during the pre-exposure and post-exposure trials was always binocular and, for the second group, viewing in the pre-exposure and post-exposure conditions was always monocular. Notice, however, that during the telestereoscopic exposure condition both groups were provided with binocular vision. If recalibration is limited to the manipulated binocular information, aftereffects would only occur for the subjects that were provided with binocular vision in the post-exposure trials. In addition, for the group pro-

vided with monocular vision in the post-exposure condition, the very same timing pattern is expected in the pre-exposure and the post-exposure conditions. In contrast, if the adaptive recalibration affects multiple sources, the aftereffects would appear in both the binocular and the monocular group. That is, after removing the telestereoscope, the hand would be closed later even when the manipulated binocular information was not available.

In summary, the aim of the present paper is to examine whether adaptation effects during telestereoscopic are a result of ignoring the binocular information sources of information that specify the misleading information and, instead, selecting other sources of information that lead to successful catching; or whether the adaptive change is due to some kind of recalibration between the binocular information and the movement pattern. If it is recalibration, it is anticipated that additional insight will be gained with regard to whether it is restricted to the manipulated binocular information or whether multiple information sources, including binocular and monocular optical and oculomotor information sources, are involved.

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## Materials and methods

### Subjects

Sixteen subjects (11 men and five women) participated in the experiment. The age range was 20–38 years. All participants reported having normal or corrected to normal vision, and their stereoacuity was at least 60 s/arc (Polaroid 3-D Vectograph, Titmus Optical Inc.). All were naive to the purpose of the experiment and were unfamiliar with the telestereoscope. Subjects were informed of the requirements of the experiment in both verbal and written form. They then gave their written consent to participate.

### Task and apparatus

Subjects were required to catch an illuminated ball (7 cm diameter) that approached with a fixed spatial trajectory. During the test trials, only the luminous ball was visible in an otherwise dark environment. The balls were presented using the ball transport apparatus (BallTrAp), as described in the accompanying paper of Bennett et al. (1999; see also Van der Kamp et al. 1997). In the present experiment, only one constant ball velocity of 2.0 m/s was used. The telestereoscope and the location of the hand and head were similar to that reported in the Bennett et al. (1999) study.

### Procedure and design

First, the subjects were asked to make judgements on reachability (i.e. verbal judgements in action terms) in order to test for the effectiveness of the telestereoscope in manipulating binocular disparity and vergence. To this end, the experimenter moved the illuminated ball to the subject in the completely darkened room. Subjects were requested to indicate verbally when the ball was at a distance that would enable it to be reached with an outstretched arm. However, they were not allowed to actually reach. Three judgements were made under binocular telestereoscopic viewing followed by three judgements under normal binocular viewing.

Next, the subjects were instructed on the procedure for catching and, subsequently, received a minimum of ten practice trials to become accustomed to the experimental setting. These practice trials were performed in the light under normal binocular viewing.

The subjects were instructed to hold the thumb in contact with the index finger at the start of every trial. Only after the subjects had caught the last five balls in a row were they considered to be ready for the experimental trials. In order to satisfy this criterion, two subjects received more than ten practice trials (i.e. 14 and 20). During the experimental trials, subjects were required to catch in the dark with only the ball visible. The experiment proceeded according to a pre-exposure, exposure, post-exposure design. In the exposure condition, subjects were required to catch under telestereoscopic viewing, whereas, in the pre-exposure and post-exposure conditions, normal vision was provided. In each of the three conditions, subjects performed 15 trials, followed by a 3-min break. The subjects were assigned to one of two groups: binocular or monocular viewing in the pre-exposure and post-exposure conditions. Both groups performed under binocular viewing while wearing the telestereoscope. The experiment took about 30 min.

On completion of the experimental trials, the subjects were asked to provide a verbal report on what they perceived and how they acted in the telestereoscopic viewing condition compared with normal viewing. The directed choice questions were as follows: (1) Did you perceive the ball as closer, farther, or at the same distance? (2) Did you close your hand earlier, later, or at the same time? (3) Did you perceive the ball as smaller, larger, or at the same size?

#### Recording system and data reduction

A 3-D SELSPOT monitoring system, consisting of two SELCOM 413-3 cameras was used for data recording. The SELSPOT system was pre-calibrated at the start of each experimental day to an accuracy of within a maximum of 2 mm error. The position of three infrared light sources (LEDs) fixed to the ball, the external face of the distal phalanx of the index finger and the external face of the second phalanx of the thumb finger were registered, with a sample frequency of 313.2 Hz. The reconstructed 3-D positions of the thumb and index-finger LEDs were filtered with a second-order Butterworth filter with a cut-off frequency of 10 Hz, which was applied twice in order to negate phase shift.

#### Dependent measures of catching performance

On the behavioural level, the number of catching failures was counted. The kinematic characteristics of the grasping phase of the catch were determined from the position profiles of the ball, thumb and finger (see Bennett et al. 1999). All timing measures were defined with respect to the moment of contact. Following previous work (Bennett et al. 1999; Van der Kamp et al. 1997; Savelsbergh et al. 1991), several dependent variables were used:

- moment of grass onset: the time at which the thumb and index finger were opened (i.e. the last zero-crossing of the hand opening velocity);
- moment of peak opening velocity: the time of peak opening velocity between the thumb and index finger;
- moment of hand closure: the time at which the distance between thumb and index was maximal and the hand started to close (i.e. the moment the hand opening velocity shifted from positive to negative);
- moment of peak closing velocity: the time of the peak closing velocity between the thumb and the index finger.

## Results

### Reachability judgements

The reachability judgements confirmed that the telestereoscope actually affected binocular disparity and/or vergence. An analysis of variance (ANOVA) with repeated

**Table 1** Subjects' verbal reports on distance, size and timing for the telestereoscopic condition as compared with the non-telestereoscopic condition

		Group	
		Binocular	Monocular
Distance	Farther	5	1
	Closer	1	2
	Same/don't know	2	5
Size	Larger	0	0
	Smaller	4	4
	Same/don't know	4	4
Timing	Earlier	6	4
	Later	1	1
	Same/don't know	1	3

measures showed a main effect for telestereoscope [ $F(1,15)=125.4$ ,  $P<0.001$ ]. That is, the actual distance that the ball was perceived as being just reachable was significantly larger under telestereoscopic viewing (mean 93.4 cm) than under normal binocular (67.4 cm). In other words, under telestereoscopic viewing, the balls appeared closer. This difference was present in all subjects.

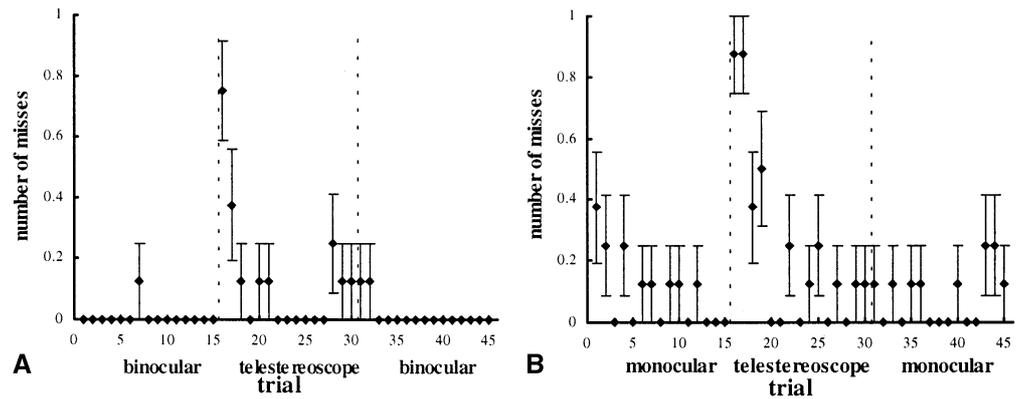
### Verbal reports

Table 1 shows the subjects' verbal reports comparing catching under telestereoscopic exposure with normal viewing conditions. Only three subjects verbally reported that they saw the ball closer when wearing the telestereoscope. This sharply contrasts to findings for the reachability judgements, where the subjects were required to assess the situation in terms of their action capabilities or affordances (Gibson 1979). With respect to timing the catch, ten subjects correctly reported to have closed their hand too early during telestereoscopic viewing. Although the other six subjects knew that they had missed the ball, they were unable to report why. Finally, half of the subjects (i.e., eight) reported the ball to be smaller.

### Catching

Figure 1 shows the intra-individual mean number of catching failures for both groups for each trial separately. Under telestereoscopic viewing, thirteen and ten subjects missed the first and second ball (i.e., trial 16 and 17), respectively. However, the subjects quickly adapted to telestereoscopic viewing, such that they successfully caught the remaining balls. No increase in the number of catching failures was found after removing the telestereoscope (i.e. trials 31–45). Figure 2 represents the means for each consecutive trial for the timing parameters of the catch for both groups. It shows that the timing of the catch was most clearly affected for the first few trials (i.e. trial 16–18) under telestereoscopic viewing,

**Fig. 1** The mean number of catching failures for the binocular (*left panel*) and the monocular (*right panel*) for each trial. The *error bars* represent the between-subject standard errors. A mean number of catching failures equaling 1 means that all eight subjects missed the ball, and a mean number of catching failures of 0 indicates that all eight subjects were successful



with the hand being opened and closed earlier. Like the number of balls missed, the timing pattern was quickly adjusted to the telestereoscopic manipulation (i.e. trial 16–30), in particular for the moment of hand closure. In the first few trials after the removal of the telestereoscope (i.e. trials 31–33), a negative aftereffect occurred for the closing of the hand, which diminished after a few trials. Finally, the adaptation and the occurrence of the aftereffects appeared qualitatively the same for both the binocular and monocular group, albeit with the variation (as represented in Fig. 2 by the error bars) being larger for the monocular group.

To examine whether adaptation to telestereoscopic viewing involved a process of recalibration or selection, the occurrence of aftereffects will be considered. To address this issue, differences between the final pre-exposure (i.e. trial 13–15), the first (i.e. 16–18) and final telestereoscopic (i.e. 28–30), and the first post-exposure trials (i.e. 31–33) will be considered for both the number of misses and the parameters for the timing pattern. Differences between the final pre-exposure and first exposure (i.e. telestereoscopic) trials would indicate an effect of telestereoscopic viewing. Differences between the first and final telestereoscopic would indicate adaptation. Differences between the first post-exposure and the final pre-exposure and telestereoscopic trials would indicate recalibration. To this end, the intra-individual means of all dependent variables were submitted to a two (group: binocular vs. monocular)  $\times$  three (condition: pre-exposure, exposure, post-exposure)  $\times$  two (block: first, final) analysis of variance (ANOVA) with repeated measures on the last two factors. Post-hoc comparisons were conducted with Tukey's HSD test ( $P < 0.05$ ).

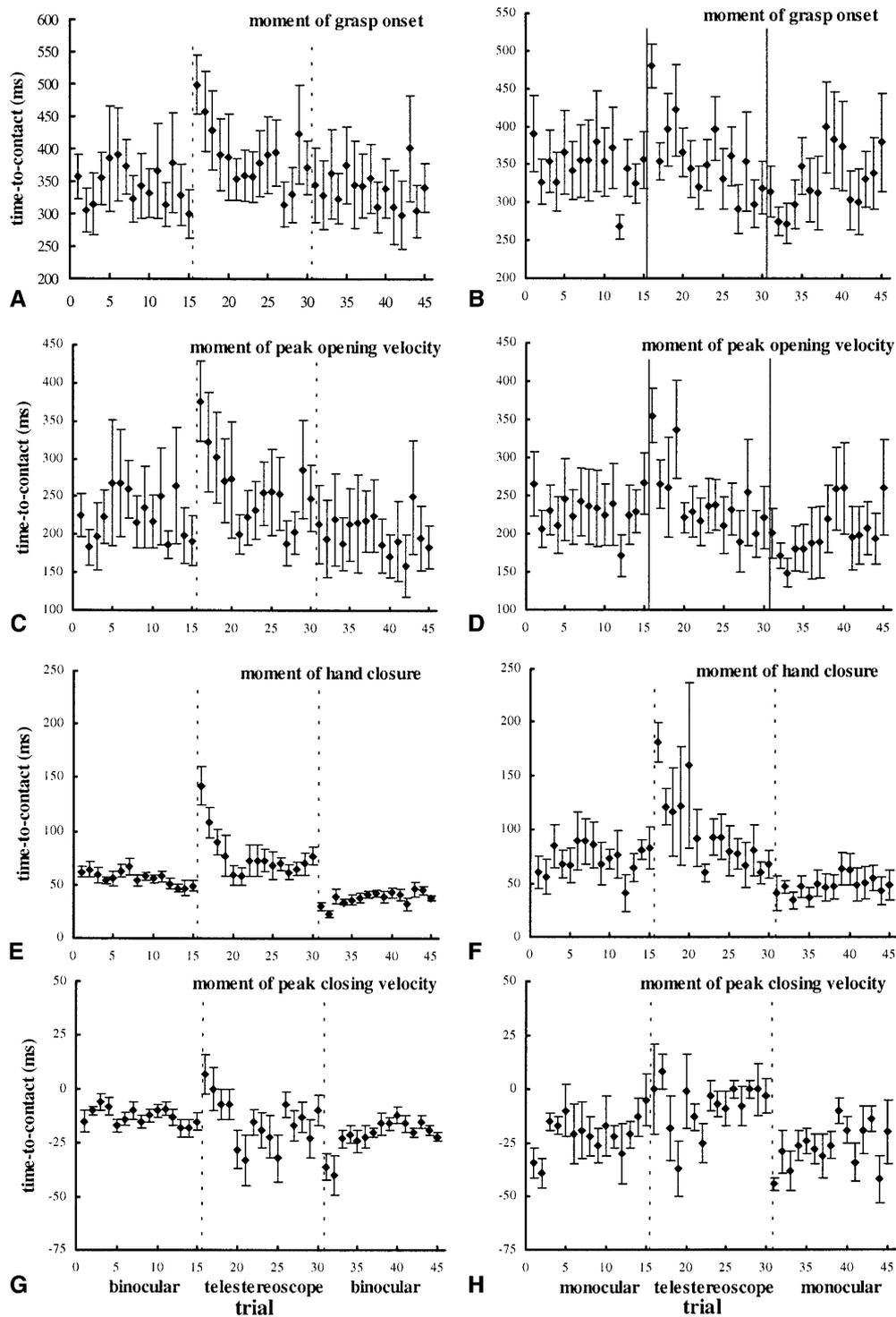
For the number of misses, significant effects of group [ $F(1,14)=5.11$ ;  $P=0.04$ ], condition [ $F(2,28)=15.27$ ,  $P < 0.001$ ], block [ $F(1,14)=43.81$ ,  $P < 0.001$ ], block  $\times$  group [ $F(1,14)=6.48$ ,  $P=0.02$ ], condition  $\times$  block [ $F(2,28)=9.25$ ,  $P < 0.001$ ] and a group  $\times$  condition  $\times$  block [ $F(2,28)=3.41$ ,  $P=0.04$ ] were discerned. Post-hoc tests showed that most balls were missed in the first three telestereoscopic trials. Moreover, the performance of the monocular subjects decreased more in the first telestereoscopic trials than by the binocular subjects (i.e., 2.1 vs. 1.3 misses out of 3 trials) (see Table 2).

With respect to the kinematics of grasp, significant effects of condition [ $F(2,28)=13.18$ ,  $P < 0.001$ ] and condition  $\times$  block [ $F(4,56)=9.78$ ,  $P < 0.001$ ] were found for the moment of grasp onset. Tukey's HSD indicated that, in the first trials of telestereoscopic viewing, the hand was opened earlier (cf. Table 2 and Fig. 2a, b). For the moment of peak opening velocity, significant effects of condition [ $F(2,28)=25.11$ ,  $P < 0.001$ ] and condition  $\times$  block [ $F(2,28)=9.29$ ,  $P < 0.001$ ] were found. Subjects reached the moment of peak opening velocity earliest in the first three trials of telestereoscopic viewing. In addition, the moment of peak opening velocity occurred significantly later in the first three post-exposure trials than in both the first and final exposure trials (cf. Table 2 and Fig. 2c, d).

For the moment of hand closure, significant effects were revealed for condition [ $F(2,28)=36.48$ ,  $P < 0.001$ ], block [ $F(1,14)=37.70$ ,  $P < 0.001$ ] and condition  $\times$  block [ $F(2,28)=39.91$ ,  $P < 0.001$ ]. Post hoc comparisons indicated that, in the first trials of telestereoscopic viewing, the hand was closed earliest. Moreover, hand closure occurred later during the first block of the post-exposure condition than during both blocks in the pre-exposure and the telestereoscopic viewing condition (cf. Table 2 and Fig. 2e, f). With respect to the moment of peak closing velocity, a significant main effect of condition [ $F(2,28)=29.32$ ,  $P < 0.001$ ] was found. The condition  $\times$  block interaction [ $F(2,28)=3.09$ ,  $P=0.06$ ] was not significant. Post-hoc comparisons indicated that the moment of peak closing velocity was reached earliest for the telestereoscopic viewing and latest for the post-exposure condition, that is, after removing the telestereoscope (cf. Table 2 and Fig. 2g, h). In short, aftereffects were observed for the moment of peak opening, the moment of hand closure and the moment of peak closing velocity, suggesting recalibration instead of selection.

The next issue is whether recalibration is restricted to binocular information or whether other information sources are involved in the process of adaptation. That is, were the aftereffects specific for the binocular group only? Seven subjects in the binocular group closed their hand later in the first post-exposure trials than in the final pre-exposure and exposure trials (the other subject closed her hand later in the post-exposure condition only in comparison with the final telestereoscopic trials). Five

**Fig. 2A–H** The mean time-to-contact (in ms) for the binocular group (*left column*) and the monocular group (*right column*) for each trial. *Error bars* represent the between-subject standard errors. Note that the *minus signs* indicate occurrence after ball-hand contact



subjects in the monocular group also showed this pattern. For the remaining three subjects, the first post-exposure trials only differed from the final pre-exposure trials and not from the final telestereoscopic trials. A significant group  $\times$  condition  $\times$  block interaction was revealed for the moment of hand closure [ $F(2,28)=4.48$ ,  $P=0.02$ ]. Post-hoc comparisons showed that the monocular group started to close their hand earlier than the binocular group in the last trials of the pre-exposure condi-

tion and during the first trials of telestereoscopic viewing (see Table 2a, b; Fig. 2e, f). Finally, for the moment of peak closing velocity, a significant group  $\times$  block interaction [ $F(1,14)=8.20$ ,  $P=0.01$ ] was found, indicating that the monocular group reached the moment of peak closing velocity earlier in the first trials than in the final trials. This difference was not present for the binocular group. In summary, aftereffects for the closure of the hand were found in both groups.

**Table 2a** The mean number of catching failures (out of three) and the means for the timing parameters of binocular group. "Exposure" represents the telestereoscopic viewing condition. Note that

Dependent variables	Pre-exposure		Exposure		Post-exposure	
	Trial 1-3	Trial 13-15	Trial 16-18	Trial 28-30	Trial 31-33	Trial 43-45
Number of misses	0	0	1.3	0.5	0.3	0
Moment of grasp onset	337	340	462	358	340	341
Moment of peak opening velocity	232	238	352	272	229	229
Moment of hand closure	62	48	113	71	30	43
Moment of peak closing velocity	-10	-18	0	-15	-33	-19

the means for the moments of grasp onset, peak opening velocity, hand closure and peak closing velocity are in ms before ball-hand contact. *Minus signs* denote occurrence after ball-hand contact

**Table 2b** The mean number of catching failures (out of three) and the means for the timing parameters of monocular group. "Exposure" represents the telestereoscopic viewing condition. Note that

Dependent variables	Pre-exposure		Exposure		Post-exposure	
	Trial 1-3	Trial 13-15	Trial 16-18	Trial 28-30	Trial 31-33	Trial 43-45
Number of misses	0.6	0	2.1	0.3	0.3	0.5
Moment of grasp onset	360	342	411	319	282	344
Moment of peak opening velocity	227	218	285	212	148	200
Moment of hand closure	72	77	139	69	40	49
Moment of peak closing velocity	-24	-13	-4	-1	-36	-27

the means for the moments of grasp onset, peak opening velocity, hand closure and peak closing velocity are in ms before ball-hand contact. *Minus signs* denote occurrence after ball-hand contact

## Discussion

### Selection and recalibration

Catching performance deteriorated during binocular telestereoscopic viewing due to an early opening and closure of the hand (cf. Bennett et al. 1999; Judge and Bradford 1988). This finding confirms the importance of binocular information in interceptive timing tasks. However, the subjects adapted remarkably quickly, such that performance recovered after only two or three trials. This was reflected in typical learning curves observed for the temporal kinematics of the catch (Fig. 2).

The present study sought to find whether the observed adaptation involved neglecting binocular information and subsequently selecting a monocular information source, or whether adaptation involved a recalibration of the coupling between information and movement. That is, rescaling the critical informational value at which the hand was opened and closed (cf. Schöner 1994). Therefore, a pre-exposure, exposure, post-exposure design was used. The findings show clear negative aftereffects for the timing of hand closure. In other words, similar to work reported by Judge and Bradford (1988), after removal of the telestereoscope, the hand was closed later. This indicates that recalibration, rather than selection, operates during the adaptation to telestereoscopic viewing. Due to catching failure in the initial exposure trials, subjects learned to close their hand later by increasing the critical value of the information. This increased critical value, in turn, led to closing the hand later in the post-exposure condition.

The phenomenon of selection, however, was also present in the present study. When the subjects in the monocular group were first exposed to telestereoscopic viewing, their timing was clearly influenced. In other words, these subjects guided their action with binocular information, by shifting from using monocular information alone. Thus, it seems that subjects are strongly attracted to binocular information, even when it incorrectly specifies the events in the environment. Therefore, it may be proposed that the occurrence of selection rather than recalibration may depend on the relative strength of the coupling between either binocular (from habit) or monocular sources of information and the grasping pattern.

The subjects' verbal reports showed a discrepancy with the observed kinematics. That is, almost 40% of the subjects were not able to explain how they improved performance during catching, and more than 75% of the subjects wrongly assessed the apparent distance of the ball (cf. Table 1). Hence, the recalibration would not seem to be determined by conscious cognitive mediation. This is in alignment with a recent proposal by Milner and Goodale (1995), who put forward that the neuroanatomically separate ventral (i.e. infero-temporal cortex) and dorsal (i.e. posterior parietal cortex) projection systems are differently involved in vision. Whereas, according to Milner and Goodale (1995), the former "builds a representation of the world", the latter serves to guide action. It appears that the observed adaptation to telestereoscopic viewing in timing the catch is supported by the dorsal projection system, while the verbal reports on tim-

ing, distance and size are based on the ventral projection system. Paradoxically, the reachability judgements under telestereoscopic viewing are consistent with the observed timing patterns, but not with verbal reports on the perceived distance of the ball. This may be due to the nature of the judgement made by the subjects. The reachability judgements, which were made in terms of action capabilities or affordances (Gibson 1979; Warren 1984), may have been less susceptible to cognitive interference. In contrast, the verbal reports on distance probably result from size-constancy. The apparent decrease in the size of the ball may have made the subjects report that the ball is at a farther distance. Others have shown that an increase of convergence is associated with an apparent decrease in size of the object (Collewijn and Erkelens 1990; Mon-Williams et al. 1997).

#### Recalibration: single or multiple sources

The second important finding is that the occurrence of the negative aftereffects was not limited to the binocular vision group. That is, the delay in hand closure after removal of the telestereoscope was observed in both the binocular and monocular groups (cf. Fig. 2e, h), although three subjects in the latter group did fail to show an aftereffect. Judge and Bradford (1988) did not find a decrement in catching performance under monocular vision after removal of the telestereoscope. These contradictory findings may be due to the nature of the task: a delay in hand closure does not necessarily lead to an increase in the number of catching failures – as in fact is the case in the present study. In other words, the global performance measure utilised by Judge and Bradford (1988) possibly obscured the aftereffect during monocular vision. The small change in phoria after adaptation, reported by Judge and Bradford (1988), points in the same direction. In sum, the observation of an aftereffect for the monocular group (i.e. in the absence of binocular information), strongly suggests that the recalibration of the coupling between information and movement is not restricted to binocular information (e.g. disparity and/or vergence), but includes monocular information (i.e. optical expansion, accommodation) as well (cf. Heuer 1993; Tresilian 1994).

Regan (Gray and Regan 1996; Regan 1997) showed that, when pitting the expansion of optical size against the change of disparity, the perception of motion in depth is lost or disrupted. Tresilian (1994; see also Wann and Rusthon 1995) proposed that timing pattern may just reflect a simple summation, with possibly a differential weighting of the two sources. He argued that, by a process of evaluation, weights are assigned to the different sources of information, with the weights being functions of perceptual information (e.g. ball size). Adaptation, then, may reflect a change in the weights assigned to the separate sources. However, as the present results demonstrate, the recalibration is not restricted to a single information source, but multiple information is involved. Ad-

aptation of the temporal catching pattern during telestereoscopic viewing, therefore, is not just a consequence of a stronger reliance on monocular information. It follows that during adaptation the assignment of weights to the various sources must be interdependent. That is, the change of the weight of a single variable is dependent on the change of the weight of another source. This increases the complexity of the process of evaluation dramatically. With each catch, the critical margin of the implied binocular information for the temporal movement form is adjusted. As a consequence, simultaneously, a change also occurs in the relation between the movement pattern and monocular optical and oculomotor sources of information. Thus, during exposure, not only is the coupling between binocular information and the grasping movement effected, but the coupling between the grasping movement and the other information sources is also recalibrated. In the post-exposure trials, therefore, a different critical margin from the pre-exposure trials will emerge when the manipulated binocular information is not available<sup>1</sup>.

#### Sources of information involved

Increasing the interocular separation when wearing the telestereoscope was found to effect the temporal pattern of the catch in binocular viewing only (Bennett et al. 1999). Thus, in contrast to recent arguments of Servos and Goodale (1998), binocular information is involved in the regulation of interceptive timing. Because it was shown that adaptation to telestereoscopic viewing is a process of recalibration of information and movement, these optical variables must be the prime sources involved in this adaptive recalibration. However, since telestereoscopic viewing also affects accommodation and vergence, it remains to be settled whether these oculomotor sources are involved as well in the adaptive recalibration.

Bennett et al. (1999) also found that the effects of telestereoscopic viewing on the timing of the catch were only apparent for the slower ball velocity at the moment of grasp onset of the catch, whereas, at the moment of hand closure, telestereoscopic viewing affected the timing independent of ball velocity. That is, increasing the interocular separation only affected the timing of the one-handed catch when the ball was within arm's range. In the present experiment, the aftereffects were only observed from the moment of peak opening velocity, that is, within reaching distance (i.e. at about 70 cm), and not for the onset of the grasp (at about 90 cm). Collewijn and Erkelens (1990) argued that, despite being fairly inaccurate, the angle of convergence might contribute to the perception of distance. For the perception of motion in depth, the results are less clear cut. Erkelens and col-

<sup>1</sup> Such an adaptive recalibration may possibly be modelled in terms of an interaction (e.g. competition and cooperation) between different attractors (cf. Kelso 1995; Schöner 1994).

leagues (Erkelens and Collewijn 1985; Regan et al. 1986) have argued that relative disparity is required, while Heuer (1993) demonstrated that changing vergence might have been involved. In the present experiment, half of the subjects from both the binocular and monocular group reported the ball to appear smaller during telestereoscopic viewing. This is consistent with recent reports that an increase in vergence leads to the object appearing smaller (e.g. Collewijn and Erkelens 1990; Mon-Williams et al. 1997). Assuming, therefore, that vergence is indeed manipulated by the telestereoscope, a finding of no aftereffects for the monocular group would have excluded the involvement of oculomotor sources of information, such as the angle of convergence or accommodative vergence in the recalibration. However, the presence of the aftereffects during the closure of the hand for both binocular and monocular vision and its absence at the moment of grasp onset, together with the findings of Bennett et al. (1999), do not entirely rule out that changing vergence is involved in the guidance of interceptive timing.

To conclude, the adaptation to telestereoscopic viewing in the timing of a one-handed catch is due to the recalibration of the coupling between information and movement, rather than a selection of another source of information. This recalibration is not restricted to the single manipulated variable, but affects multiple information encompassing binocular (e.g. disparity, changing disparity, angle of convergence and changing vergence) and monocular (e.g. optical expansion, accommodation) optical and oculomotor sources.

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