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Multiple information sources in interceptive timing

John van der Kamp [a,b,*], Geert Savelsbergh [a,b], Jeroen Smeets [c]

[a] *Research Institute for Fundamental and Clinical Human Movement Sciences, Van der Boechortstraat 9, 1081 CT Amsterdam, The Netherlands*

[b] *Faculty of Human Movement Sciences, Free University, Amsterdam, The Netherlands*

[c] *Department of Physiology, Erasmus University, Rotterdam, The Netherlands*

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Abstract

This study was designed to explore the limitations of tau (τ) as an explanatory construct for the timing of interceptive action. This was achieved by examining the effects of environmental structure and binocular vision on the timing of the grasp in a simple one-handed catch. In two experiments, subjects were required to catch luminous balls of different diameters (4, 6, 8 and 10 cm) in a completely darkened room. In the first experiment the influence of the presence vs. absence of an environmental background structure (both under monocular viewing) was tested, and in the second experiment the influence of monocular vs. binocular vision was examined. It was found that irrespective of the presence of environmental structure, an effect of ball size occurred in the monocular viewing conditions. That is, in monocular viewing conditions the grasp was initiated and completed earlier for the larger balls as compared to the smaller ones, while in the binocular viewing condition subjects behaved in accordance with a constant time to contact strategy: no effects of ball size were found. It is concluded that under binocular viewing a binocular information source is used, while in the monocular viewing condition a lower order information source like image size or image velocity is probably involved. © 1997 Elsevier Science B.V.

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[*] Corresponding author. E-mail: J_van_der_Kamp@fbw.vu.nl.

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1. Introduction

Recently, there has been a considerable interest in the visual guidance of interceptive actions such as catching, hitting and striking. In catching, e.g., not only information about where and when to intercept the ball (e.g. Michaels and Oudejans, 1992; McLeod and Dienes, 1993; Peper et al., 1994; McBeath et al., 1995), but also information for final hand adjustments to enclose the ball is necessary; that is, information about when to open and close the hand (e.g. Savelsbergh et al., 1991, 1993; Wann and Rushton, 1995).

Most research in this respect has focused on information generated by the approaching object. Lee (1976) showed that the inverse of the relative rate of optical expansion of an approaching object directly specifies time to contact. Although many investigators have sought to provide evidence for the use of this optical variable tau (τ), most studies are mainly descriptive in nature (Lee et al., 1983; Sidaway et al., 1989; Savelsbergh et al., 1992), showing that subjects behaved in accordance with a constant time to contact or tau-margin strategy. Since the available information sources are not usually manipulated, these studies are necessarily restricted in providing an answer as to whether tau contributes to the visual guidance of interceptive action (cf. Wann, 1996). A more direct test of the contribution of tau, therefore, is the direct manipulation of the relative rate of expansion. To this end, Savelsbergh (Savelsbergh et al., 1991, 1993) required subjects to catch balls of constant size and balls that deflated during approach. Results show that in the case of the shrinking balls, the grasp occurs more closely before ball–hand contact, as specified by the smaller relative rate of expansion, leading Savelsbergh et al. (1991) to argue that the grasping phase of the catch is controlled by tau.

Although the evidence supporting the importance of tau in the control of timing in interceptive actions seems to be extensive, none of the experiments actually prove the use of this variable. Even the experiments of Savelsbergh et al. (1991, 1993), which come closest to proving the use of tau, do not rule out the possibility that other co-varying variables contribute to interceptive timing. That is, when deflating balls, not only is tau changed, but also the size of the retinal image and the retinal expansion. Indicative in this respect is that a recent series of studies using computer simulated environments reported what DeLucia (DeLucia, 1991; DeLucia and Warren, 1994) denoted the 'size-arrival' effect. That is, the larger the approaching object, the nearer in time it is perceived (Caird and Hancock, 1994; DeLucia, 1991; DeLucia and Warren, 1994; Heuer, 1993; Oudejans et al., 1993a, b; Stewart et al., 1993). Since an important assumption in the tau hypothesis is that the perception of time to contact should be *independent* of object size, tau being the *relative* rate of optical expansion, these results are not anticipated by this hypothesis. However, when sources that potentially provide distance information such as ground intercept (DeLucia, 1991) or disparity/ocular vergence (Heuer, 1993) were added, the effects of object size weakened or disappeared. These findings challenge the assumption that the time to contact judgements are uniquely based on the relative rate of expansion or tau and suggest that information sources related to disparity or ground intercept, and presumably specifying time to contact, might contribute as well.

In the above-mentioned studies, however, observers were looking binocular to a 'monocular environment'. Thus, providing ground intercept information or stereoscopic displays resulted not only in additional information, but might also have (partly) reduced potentially conflicting information. Moreover, it should be taken into account that, except in the DeLucia and Warren (1994) study, simulations were such that the approaching objects disappeared before actually reaching the subject, that is, the objects 'left' the screen. As a consequence, subjects were required to make their time to contact judgements from memory, whereas in natural interceptive action visual information is available during the whole act minus the visuo–motor delay. In other words, unlike computer simulated environments, an oncoming object generates visual information, which could be used to continuously guide the act until about 100 ms before contact (Lee et al., 1983; Bootsma and Van Wieringen, 1990; Smeets and Brenner, 1995a). Another difficulty in generalizing the findings of these studies to intercepting solid objects in the natural environment is the nature of the response. In contrast to the highly ballistic button press task, interceptive actions allow for a continuous adjustment of the movement, resulting in a markedly higher temporal accuracy (cf. Bootsma, 1989). The question, thus, arises whether the size-arrival effects occur in natural interceptive actions such as catching, and if so, whether these are specific to the presence of different information sources.

More generally, to establish whether interceptive timing is solely based on tau, the effects of manipulating information sources other than tau, need to be considered. Hence, the tau hypothesis should also be tested without varying tau. In other words, not only the alter-tau alter-action (Michaels and Beek, 1995), but also the not-alter-tau not-alter-action logic should be evaluated. Very few studies, however, have examined the control of interceptive action on the basis of tau in conjunction with information sources originating from, for instance, environmental structure (e.g. relative size) and binocular vision (e.g. disparity) as compared to monocular vision, and as such, the limitations of tau as an explanatory construct are largely unknown. The literature will be reviewed in this respect.

Rosengren et al. (1988) and Savelsbergh and Whiting (1988) found a decrement in catching performance when environmental information was degraded. Both studies show that this decrement in catching performance was primarily due to an increase in temporal errors (Rosengren et al. (1988) did not explicitly examine the number of temporal errors, but inspection of their Table 1 shows 61% of the unsuccessful catches to be temporal errors), suggesting that background structure is used to control interceptive timing. This is in direct contradiction with the tau hypothesis, in which an often implicit assumption states that, since the relative rate of optical expansion originates from the approaching object, information from the environment should not affect the timing of interceptive action. The role of environmental information in controlling body sway (Rosengren et al., 1988) and different perceived distances of the ball due to differences in contrast between ball and background (Savelsbergh and Whiting, 1988; Koslow, 1985) were invoked to explain the decrement in catching performance. Only the former explanation was examined and could be ruled out, since the amount of body sway and catching performance were only correlated for the full light condition (Rosengren et al., 1988). Studies using computer simulated environments are somewhat equivocal with respect to the role of environmental structure in time to contact judgements. For instance, DeLucia (1991) showed that subjects did not use a constant time to contact strategy when relative size information was present. Moreover, Schiff and Detwiller (1979) found that only for approaches from larger distances the timing was more accurate when background texture was present in case of larger time to contacts. In contrast, the temporal properties in hitting laterally moving targets are shown to be influenced by (moving) background structure (Smeets and Brenner, 1995b; Brenner and Smeets, 1996). Taken together, previous research suggests an increment in catching performance when environmental information sources are available, particularly in the temporal domain. But, it remains unclear whether the timing is indeed affected by environmental information, and if so, what specific information source (e.g. relative size or relative motion) is involved in such a case.

Another assumption of the tau hypothesis is that it is essentially a monocular information source. Consequently, no differences in the temporal characteristics of interceptive actions should exist when comparing monocular and binocular vision. However, studies reporting constant time to contact strategies often provided subjects with binocular vision only, thereby making additional information sources such as disparity available (e.g. Lee et al., 1983; Sidaway et al., 1989; Savelsbergh et al., 1992). The reason for using binocular instead of monocular vision is often not stated. Some studies, however, did report influences of binocular information on the timing of interceptive action. For example, in a catching task Judge and Bradford (1988) manipulated disparity by using a telestereoscoop, that is, by enlarging the effective interocular distance. As these authors expected, most subjects closed their hands too early; increasing ocular separation results in an increase in disparity specifying a shorter target–perceiver distance. But, since the subjects also had to make spatial predictions, it remains unclear whether the observed early closing of the hand is due to temporal or spatial errors. In addition, Savelsbergh et al. (1991) found more pronounced differences between the deflating balls and the constant balls under monocular as compared to binocular viewing. This indicates that whenever binocular information sources are available these may contribute to the regulation of the temporal characteristics of the catch (Savelsbergh, 1995). The findings of Wann and Rushton (1995), in which subjects caught balls in a virtual environment, stress the same point. Contradictory results, however, are reported by Bootsma and Van Wieringen (1988), who examined a skilled table tennis player and found the timing of an attacking forehand drive in table tennis to be similar under monocular and binocular vision. In sum, although some evidence for the contribution of binocular vision (i.e., information sources related to target vergence or absolute disparity) in the timing of interceptive actions such as catching is available, its precise contribution still remains unclear.

The aim of the present paper, therefore, is to examine whether interceptive timing is uniquely controlled by tau or whether information sources generated by environmental structure and binocular vision also contribute. To this end two experiments were conducted in which subjects caught luminous balls of different diameters in a completely dark room. Environmental structure (background versus no background, both monocular) or viewing (binocular versus monocular, without background) were manipulated. On the one hand, the tau hypothesis predicts a constant time to contact strategy and, therefore, no differences in the timing of the catch are expected when environmental structure and binocular vision are provided or removed. On the other hand, if environmental structure and/or binocular vision actually influence interceptive timing, the role of these information sources might be twofold: First, environmental structure and binocular vision might influence interceptive timing differently from time to contact information as specified by tau.

Consequently, manipulation of these information sources may result in systematic deviations from a constant time to contact strategy, such as the size-arrival effect. Second, environmental structure and binocular vision may contribute in interceptive timing but not contradict time to contact information as specified by tau (i.e. when only monocular vision and no environmental structure is provided to the subjects). In such cases, removing these information sources may only lead to a more variable timing, albeit subjects will maintain a constant time to contact strategy.

2. Experiment 1: Catching with and without environmental structure

2.1. Methods

2.1.1. Subjects

Ten adults (eight female, two male, mean age 22.8 years, ranging from 19 to 28 years) participated in the experiment. All had normal or corrected to normal vision. Subjects were paid for their participation and were naive to the purpose of the experiment.

2.1.2. Apparatus

Four balls with diameters of 4, 6, 8, and 10 cm were used as the catching objects. The balls were painted with luminous paint and loaded before each trial. During the trials only the illuminated ball was visible in an otherwise darkened room.

The balls were presented using the Ball Transport Apparatus (BallTrAp: see Fig. 1). The BallTrAp consists of a wooden box (305 × 110 × 15 cm) containing two aluminium wheels (diameter 80 cm) with their centers at 200 cm distance and connected to each other with a rubber belt (651 cm). Fixed to the belt is a little trolley with an aluminium rod (length 58.5 cm), at the end of which the balls can be attached using velcro. One wheel is driven by a Micron MT30r4-58 Servo-Motor (maximal torque 3.5 NM and maximal speed 2500 rpm). The Servo-Motor is controlled by a Galil DMC-700 Motion Controller which receives instructions for the position and velocity of the little trolley (balls) from a PC. The BallTrAp is supported by two columns such that the wooden box is positioned 155 cm above the floor.

The subjects sat on a chair with the right arm (wrist) resting on an adjustable arm rest fixed to a table, holding the lower arm fairly rigid while giving

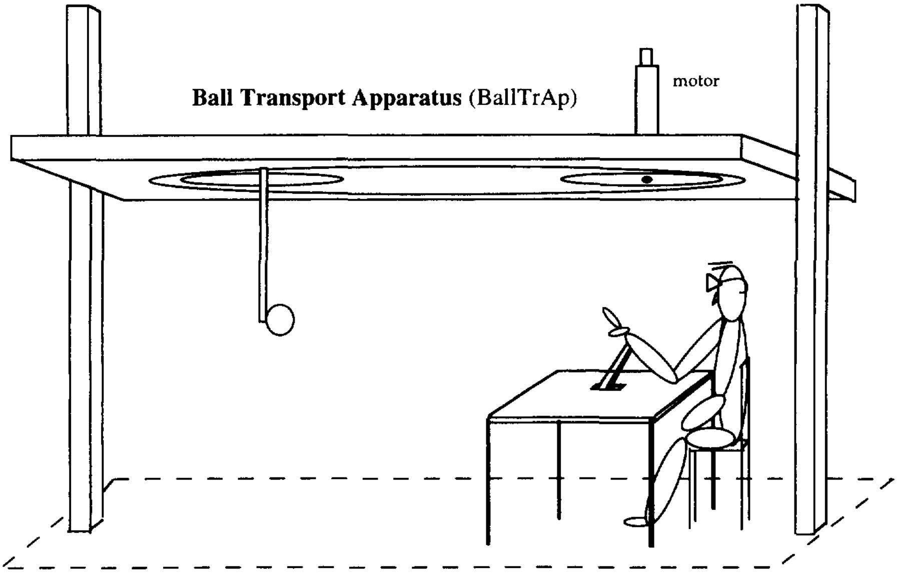

Fig. 1. The BallTrAp: The subject sat at the end of the 2.0 m straight part of the track. The ball can be transported into the right hand.

freedom to movements of the hand. In this way the arm was positioned just under the track of the little trolley at the end of its 200 cm straight part, that is, the hand was positioned in the path of the ball. The distance between eyes and hand was about 25 cm. The ball was transported into the hand. It was first accelerated to a constant velocity of 3 m/s and started to decelerate (constant 2 m/s^2) at 227 cm distance from the hand such that it stopped exactly in the hand. Immediately after ball–hand contact, the rod at which the ball was attached returned to its home position (acceleration 5 m/s^2). For technical and safety reasons, it was impossible to use constant velocity approaches. However, it is shown that also for constant accelerative and decelerative approaches the tau-strategy is used, albeit leading to an over and underestimation of the actual time to contact (Lee and Reddish, 1981; Lee et al., 1983; Tresilian, 1991, 1993). Thus, since only one approach profile was used, it can be predicted from a tau perspective that a constant time to contact strategy will hold. Furthermore, usually in catching, the hand stops at or just after the moment the ball reaches the hand, implying a deceleration of the hand and hence a deceleration of the ball relative to the hand (Alderson et al., 1974; Tresilian, 1991).

Subjects wore liquid crystal spectacles (Plato System P-1) which were also controlled by the PC, thereby synchronising vision with the position of the balls. The spectacles opened 1450 ms before ball–hand contact (i.e., at a distance of 200 cm from the hand) and remained open for 2 s. Only monocular vision was provided (right eye). Subjects wore headphones with white noise to exclude, as much as possible, the noise produced by the BallTrAp.

A wooden frame, 140 cm in height and 150 cm in width, with wire netting, served as a background structure to provide background information. The rectangles in the wire netting measured 10 × 5 cm and were painted with luminous paint. The background structure was positioned in front of the subject at a distance of 350 cm.

2.1.3. Procedure

Subjects were required to catch luminous balls with diameters of 4, 6, 8 and 10 cm in a completely darkened room. The viewing period was such that the balls were only visible during the straight line of approach. The different sized balls were projected in two blocks of 48 trials (the balls were completely randomized within each block); one with and one without background. Six subjects started with and four started without the background. After each of 24 trials there was a short break of 3 min. The whole experiment took about 60 min. No information about performance was provided by the experimenters, however, subjects could extract information about size of the balls when they had caught the ball. The subjects were required to start with the tip of the thumb and index finger touching each other.

2.1.4. Dependent variables and data analyses

A 3-D SELSPOT monitoring system, consisting of two SELCOM 413-3 cameras, was used for data registration. By means of this system, the position of four infra-red light sources (LEDs) fixed to the end of the aluminium rod (i.e. 'ball-LED'), the first thumb and index finger phalanx, and on medial side of the hand (the musculus adductor pollicis, caput transversum) of the right hand could be registered. The position signal was sampled with a frequency of 156.4 Hz. The SELSPOT system was pre-calibrated at the start of the experiment to an accuracy of 3 mm. The subjects were instructed to hold the thumb in contact with the index finger at the start of every trial. 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.

The following dependent variables were noted: (1) First, during the experiment, the number of *catching failures*, that is, the number of balls not taken from the rod, were counted for each condition; (2) the kinematics of the grasping phase of the catch were determined. For this purpose, the moment of ball–hand contact was defined as the moment at which the distance between the 'ball LED' and the 'hand LED' was minimum. Adaptation of hand aperture was determined, by calculating the distance between the thumb and index finger. All timing measures were defined with respect to the moment of ball–hand contact. Following earlier work of Savelsbergh (Savelsbergh et al., 1991, 1993; Polman et al., 1996), the following dependent variables were used.

Onset of the grasp: the time before ball–hand contact at which the hand was opened (start increase thumb–index finger distance).

Moment of maximal aperture: the time before ball–hand contact at which the hand started to close (at maximal thumb–index finger distance).

Moment of the completion of the catch: the time before (or after) ball–hand contact at which the ball was caught (no decrease of thumb–index finger distance).

Maximal aperture: the maximal distance between thumb and index finger at moment of closing the hand.

Peak opening velocity: the maximal velocity of the opening of the hand.

Peak closing velocity: the maximal velocity of the closing of the hand.

For each subject the means and standard deviation in each condition were calculated for all dependent variables. A 2(group: no background first vs. background first) × 2(environment: no background vs. background) × 4(ball size: 4 vs. 6 vs. 8 vs. 10 cm) analysis of variance (ANOVA) with repeated measures on the last two factors was carried out on the means and standard deviations. For the main effects post-hoc comparisons were conducted with Tukey's HSD test ($p < 0.05$), while for interaction effects means were compared using Scheffé's S method ($p < 0.05$).

2.2. Results

2.2.1. Catching failures

As Fig. 2 illustrates, the 4 cm balls were most frequently missed, irrespective of the presence of the background. In an analysis of variance this was reflected by a significant main effect for ball size ($F(3,24) = 22.00$, $p < 0.001$), but not for environment ($F(1,8) = 1.28$) and environment × ball size ($F(3,24) = 0.26$). Post hoc indicated that fewer 4 cm balls were caught

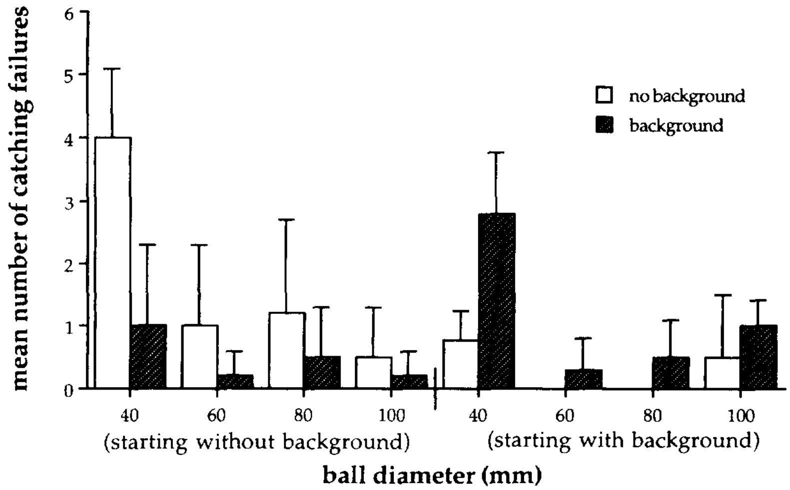

Fig. 2. Number of catching failures for the different balls in the background and nonbackground condition specified for the two groups of subjects.

as compared to 6, 8 and 10 cm balls. Furthermore, the analysis of variance revealed significant interaction effects of environment × group ($F(1,8) = 33.38$, $p < 0.001$) and environment × ball size × group ($F(3,24) = 4.02$, $p < 0.05$). Post hoc indicated that when starting without background, more balls were missed in the non-background condition, while the group that started with the background missed most balls in the background condition. Thus, most balls were missed in the first part of the experiment. In addition, during this first part of the experiment, the group that started without the background caught the 4 cm ball less often than the 10 cm ball, while no differences between ball sizes were found significant for the subjects who started with background.

2.2.2. Temporal characteristics: Effects of ball size and environment

As can be seen from Table 1, a trend existed, such that the larger the ball the earlier the subjects opened and closed the hand and caught the balls, i.e., a size-arrival effect occurred. This was reflected in significant main effects of ball size for the moment of onset of the catch ($F(3,24) = 27.63$, $p < 0.001$), the moment of maximal hand aperture ($F(3,24) = 10.69$, $p < 0.001$) and the moment of completion of the catch ($F(3,24) = 15.39$, $p < 0.001$). Post hoc indicated that with respect to the moment of onset of the catch, all means differed significantly, except those for the 4 and 6 and 4 and 8 cm balls. The

Table 1
Means and standard deviations for all kinematic dependent variables (Experiment 1)

Dependent variable	Environmental structure	Ball size					*F*-value	
		40 mm	60 mm	80 mm	100 mm		Mean	SD
Moment of onset	No background	675 (121)	667 (113)	717 (14)	793 (101)	713 (112)	E: 6.83^{*}	E: 1.25
	Background	623 (108)	583 (111)	668 (98)	749 (91)	655 (102)	B: 27.63^{***}	B: 3.27^{*}
		649 (114)	625 (112)	692 (106)	771 (96)		E × B: 1.95	E × B: 0.37
Moment of maximal hand aperture	No background	270 (113)	278 (127)	305 (125)	347 (151)	301 (128)	E: 0.15	E: 6.12^{*}
	Background	279 (101)	253 (96)	300 (100)	358 (137)	297 (113)	B: 10.69^{***}	B: 5.13^{**}
		274 (108)	265 (112)	303 (112)	359 (144)		E × B: 1.55	E × B: 0.58
Moment of completion of the catch	No background	−83 (69)	−61 (64)	−57 (66)	−8 (65)	−52 (66)	E: 2.77	E: 0.11
	Background	−66 (57)	−47 (53)	−41 (60)	−6 (82)	−40 (64)	B: 15.39^{***}	B: 1.76
		−74 (63)	−54 (58)	−49 (63)	−7 (74)		E × B: 0.29	E × B: 4.00^{*}
Maximal hand aperture	No background	127 (14)	134 (14)	142 (11)	145 (12)	137 (13)	E: 0.62	E: 0.00
	Background	130 (12)	136 (13)	143 (12)	150 (11)	139 (12)	B: 19.07^{***}	B: 1.63
		128 (13)	135 (13)	142 (12)	148 (12)		E × B: 1.33	E × B: 0.39
Peak opening velocity	No background	692 (216)	767 (231)	828 (240)	869 (273)	789 (240)	E: 2.39	E: 3.17
	Background	752 (238)	859 (267)	863 (266)	993 (311)	867 (270)	E: 11.91^{***}	B: 4.43^{*}
		722 (227)	813 (249)	845 (253)	931 (292)		E × B: 1.87	E × B: 0.10
Peak closing velocity	No background	761 (247)	631 (228)	487 (203)	399 (153)	558 (207)	E: 0.31	E: 0.30
	Background	682 (290)	593 (221)	425 (151)	402 (224)	526 (221)	B: 17.25^{***}	B: 1.57
		699 (268)	612 (224)	456 (176)	40 (188)		E × B: 0.47	E × B: 1.88

Note: Moment of initiation, moment of maximal hand aperture and moment of completion of the catch in milliseconds before ball–hand contact (i.e., minus signs indicate occurrence after contact!). Maximal hand aperture in millimeters, and peak opening and closing velocity in millimeters per second. The *F*-values for the main effects of Environmental structure (E) and Ball size (B), and the interaction of Environmental structure × Ball size (E × B) are indicated.
$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

moment of maximal hand aperture occurred earlier for the 10 cm ball as compared to the other balls, and the same was true for the moment the catch was completed.

The only effect for background structure was found for the moment of onset of the catch ($F(1,8) = 6.83$, $p < 0.05$). That is, subjects started to open their hand earlier when the background was not present (713 vs. 656 ms before contact). For the moment of maximal hand aperture ($F(1,8) = 0.15$) and the moment of completion ($F(1,8) = 2.77$) no such differences were found. Moreover, no interaction effects between ball size and environment approached significance.

Table 1 also shows the mean standard deviations. Significant main effects of ball size were found for the moment of initiation ($F(3,24) = 3.27, p < 0.05$) and the moment of maximal hand aperture ($F(3,24) = 5.13$, $p < 0.01$). Post hoc indicated that for the moment of initiation the standard deviation for the 10 cm was smaller than that for the 4 cm, while the moment of maximal aperture was more variable for 10 cm as compared to the other balls. Background structure significantly effected the standard deviations for the moment of maximal aperture ($F(1,8) = 6.12$, $p < 0.05$), that is, variability was larger when no background structure was present. Moreover, a significant interaction of ball size × environment was found for the moment of completion of the catch ($F(3,24) = 4.00$, $p < 0.05$). Post-hoc analysis indicated a larger standard deviation for the 10 cm ball as compared to the 6 cm ball when the background structure is available, while no such differences existed without the background.

2.2.3. *Temporal characteristics: Effects of group*

As depicted in Figs. 3 and 4 differences between the two groups existed. First, for the moment of maximal aperture interactions of environment × group ($F(1,8) = 9.18$, $p < 0.05$) and environment × size × group ($F(3,24) = 4.80$, $p < 0.01$) were found. Post hoc indicated that, irrespective of the presence of background structure, only during the first half of the experiment subjects closed their hand earlier for the largest ball as compared to the smallest ball. Thus, differences for ball size disappeared during the second half of the experiment. In addition, for the largest ball, but not for the other ones, subjects who started with the background tended to close their hand earlier as subjects who started without the background (Fig. 3).

Second, a significant environment × size × group interaction for the moment of completion of the catch existed, ($F(3,24) = 4.22$, $p < 0.05$). Post-hoc analysis indicated that during the first part of the experiment, ball size

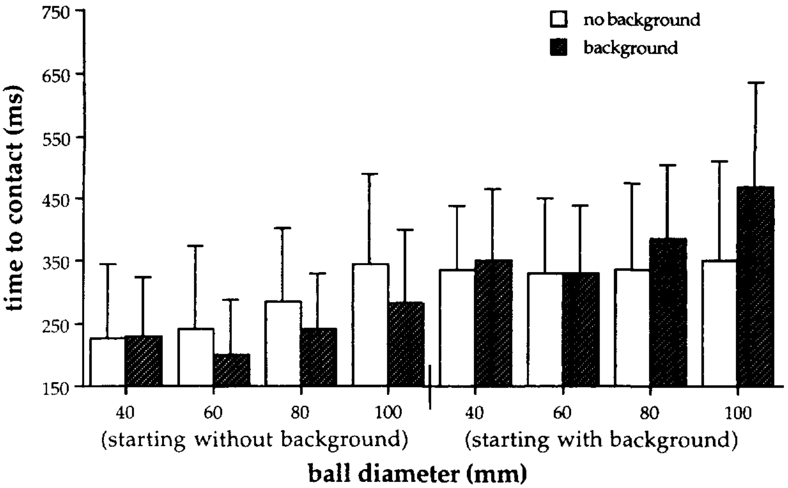

Fig. 3. Moment of maximal hand aperture for the different balls in the background and nonbackground condition, specified for the two groups of subjects.

had a more pronounced effect on the moment of completion of the catch than in the second part (Fig. 4). That is, during the first part of the experiment, it was found that for the group starting with the background the mean for largest ball differed from the means for the smaller balls, while in the second part of the experiment no differences were present. Thus, during the experiment differences in timing between the different balls diminished completely. A

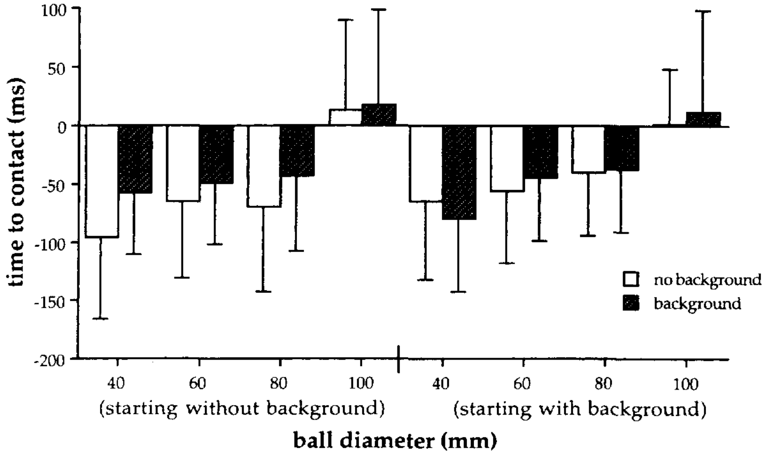

Fig. 4. Moment of completion of the catch for the different balls for the two groups of subjects.

similar trend occurred for the group starting without the background. That is, in the first part of the experiment the moment of completion of the catch for the largest ball differed from the smallest ball, while in the second part of the experiment no differences were found significant.

For the mean standard deviations, the interaction of environment × group for the moment of completion of catch was found to be significant ($F(1,8) = 6.37$, $p < 0.05$). Post hoc indicated that the subject who started without the background showed a larger variability in the background condition in comparison to subjects who started with the background (Fig. 4).

2.2.4. *Hand aperture, peak opening and closing velocity*

Table 1 reports the mean scores for the dependent variables, maximal hand aperture, peak opening and peak closing velocity. Clearly, maximal hand aperture increases with ball size, and the background did not affect maximal hand aperture. ANOVA on the maximal hand aperture did reveal a significant main effect of ball size ($F(3,24) = 19.07$, $p < 0.001$). Post hoc indicated that the maximal hand opening was larger for the larger balls as compared to the smaller ones. Furthermore, a significant ball size × group interaction ($F(3,24) = 3.82$, $p < 0.05$) showed that these differences for ball size were most pronounced for those subjects who started without the background (Fig. 5). No significant effects were found with respect to the mean standard deviations.

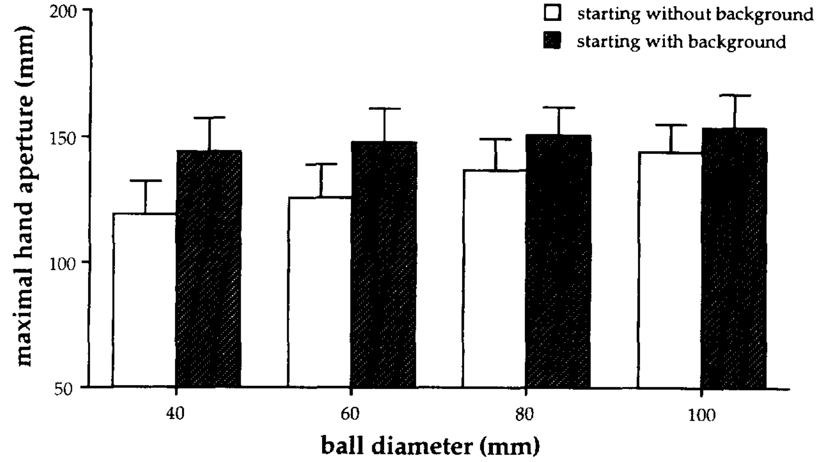

Fig. 5. Maximal hand aperture for the different balls for the two groups.

The ANOVA also revealed significant main effects of ball size for the peak opening ($F(3,24) = 11.91$, $p < 0.001$) and peak closing velocity ($F(3,24) = 17.25$, $p < 0.001$). Post hoc indicated that for increasing ball size, peak opening velocity increased, whereas peak closing velocity decreased. Furthermore, a main effect of ball size was found for the mean standard deviation of the peak opening velocity ($F(3,24) = 4.43$, $p < 0.05$). Post hoc indicated that variability was larger for the 10 cm ball than for the 4 cm ball.

2.3. Discussion

Unlike the findings reported by Rosengren et al. (1988) and Savelsbergh and Whiting (1988), adding environmental structure did not result in an increment in catching performance in the present task. No differences in the number of caught balls was found between the two environmental conditions. Thus, it seems that environmental structure does not facilitate the temporal aspects of catching performance. There may be several reasons for the discrepancy between the present results and those reported by Rosengren et al. (1988) and Savelsbergh and Whiting (1988), the most important of which probably is the rather crude index of temporal errors in the aforementioned studies. That is, an error was denoted as temporal when the ball contacted the hand but was not actually caught. Since also spatial requirements had to be fulfilled, it might be that those errors were not temporal in origin, but due to a lack of final spatial adjustments of the hand to the ball. Effects of environmental structure were also absent in the temporal kinematics. As demonstrated in computer simulated environments (e.g. Schiff and Detwiller, 1979; DeLucia, 1991), background structure does not influence the timing, which is in alignment with the tau hypothesis. The only exception was at the moment of initiation of the catch, which occurred earlier when background structure was available. Furthermore, albeit not consistently for all dependent variables, there tends to be a somewhat higher variation without the presence of environmental structure (e.g. at the moment of maximal aperture, and at the moment of completion of the catch for the group that started without background), which might indicate a minor contribution of an information source originating from the background that specifies the same information as tau, such as for instance, its complement, the relative rate of occlusion of background.

A size-arrival effect was found for both environmental conditions, that is, the larger the balls the earlier the hand was opened and closed, and the catch was completed. Thus, as in computer simulated monocular environments (e.g. DeLucia, 1991; DeLucia and Warren, 1994; Oudejans et al., 1993a, b), subjects did not act in accordance with a constant time to contact or tau-margin strategy. Clearly, the data are strongly contrasting a strict tau hypothesis. The reasons for these findings can be twofold. First, since both in the present experiments and in those using computer simulated environments only monocular information sources were available to the subjects, the size-arrival effect may be information based (and thus contrasting the tau hypothesis). If true, providing subjects with binocular vision may result in the reappearance of a constant time to contact strategy (cf. Section 1). This hypothesis will be tested in experiment 2.

Secondly, the size-arrival effect in the present experiment might also be due to the physical constraints on the task. That is, the larger the aperture required the earlier the catch must be initiated, and since the required closing distance is smaller for the larger balls (the maximal aperture is relatively smaller for the larger balls) the catch is completed earlier. However, subjects seemed to have compensated for these differences in maximal hand aperture by adapting the peak opening and closing velocity, as was also observed by Jeannerod (Jeannerod et al., 1992; Paulignan et al., 1991) for grasping different sized stationary objects. Also the difficulty in precision control might be a mediating factor in the occurrence of the size-arrival effect. Due to higher precision demands, grasping smaller objects will lead to a lengthening of the movement duration when compared to larger objects (Marteniuk et al., 1990; Paulignan et al., 1991). Since the catch is completed earlier for the larger balls, one might wonder whether the size-arrival effect is due to different accuracy demands for the different ball sizes. Table 2 shows the group means for the total grasp duration (i.e., the difference between the moment of onset and the moment of completion of the catch), the opening duration (i.e., the difference between the moment of onset and the moment of maximal hand aperture), and the closing duration (i.e., the difference between the moment of maximal hand aperture and the moment of completion of the catch). With respect to ball size, it can be seen that the smaller the ball the smaller the movement duration. A 2(environment: no background vs. background) × 4(ball size: 4 vs. 6 vs. 8 vs. 10 cm) ANOVA with repeated measures showed significant differences for the total grasp duration ($F(3,27) = 10.05$, $p < 0.001$), opening duration ($F(3,27) = 3.26$, $p < 0.05$), but not for the closing duration ($F(3,27) = 2.59$, $p = 0.07$). Thus, instead of a lengthening of the movement duration in the case of the smaller balls, the reverse occurred; the smaller the ball, the smaller the movement duration, excluding an interpretation of the size-arrival effect in terms of precision control or the speed-accuracy trade-off. Nevertheless, for the total grasp duration and the opening

Table 2
Means and standard deviations for the movement durations (Experiment 1)

Movement duration	Environmental structure	Ball size					*F*-value	
		40 mm	60 mm	80 mm	100 mm		Mean	SD
Total grasp duration	No background	763 (140)	728 (118)	776 (122)	802 (106)	767 (123)	E: 8.03*	E: 0.66
	Background	648 (110)	598 (116)	667 (110)	697 (122)	652 (114)	B: 10.05***	B: 0.36
		705 (125)	663 (117)	721 (116)	749 (116)		E × B: 0.44	E × B: 1.35
Opening duration	No background	400 (122)	389 (123)	411 (128)	444 (147)	411 (130)	E: 6.54*	E: 1.74
	Background	329 (104)	319 (105)	352 (110)	371 (139)	343 (115)	B: 3.26*	B: 2.43
		364 (113)	354 (114)	381 (119)	407 (143)		E × B: 0.11	E × B: 0.14
Closing duration	No background	355 (117)	339 (110)	363 (118)	356 (142)	353 (122)	E: 0.58	E: 10.58***
	Background	345 (95)	300 (83)	341 (104)	363 (129)	337 (103)	B: 2.59	B: 6.17**
		350 (106)	319 (96)	352 (111)	360 (136)		E × B: 1.64	E × B: 0.34

Note: All durations are in milliseconds. The *F*-values for the main effects of Enviromental structure (E) and Ball size (B), and the interaction of Environmental structure × Ball size (E × B) are indicated.

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

duration, significant main effects for environment were revealed ($F(1,9) = 8.03$, $p < 0.05$ and $F(1,9) = 6.54$, $p < 0.05$, respectively), which might indicate a contribution of background structure in precision control. In general, this suggests that in the present experiment, physical constraints are of minor importance with respect to the timing of the catch when oncoming objects differ in size. In other words, subjects strive to keep an invariant temporal pattern (see also Polman et al., 1996).

During the second half of the experiment the effects of ball size diminished at the moments of maximal hand aperture and completion of the catch. The latter was also reflected in a decrease of catching faults. Thus, with practice subjects behaved in accordance with a tau-margin strategy in the final part of the catch. Similar observations were made by Savelsbergh et al. (1996), who demonstrated that acquired tactile information from previous trials about fragility and weight of the object influenced the visual guidance of the subsequent ones. This may indicate that subjects learn to attune to a more appropriate (i.e., specifying time to contact and leading to an increment in performance) information source during the experiment. In other words, tactile information about ball diameter together with the catching failures in the first half of the experiment may have resulted in the attunement and strengthening of the use of other information sources, such as tau, during the second half of the experiment.

In sum, it was demonstrated that ball size but not environmental structure influenced interceptive timing. This strongly questions the use of tau, and hints at the involvement of lower order variables such as image size or velocity. However, since subjects were provided with monocular information sources only, the size-arrival effect may disappear when binocular information sources are available. This assumption will be examined in the second experiment.

3. Experiment 2: Catching monocular versus binocular

3.1. Methods

3.1.1. Subjects

Ten adults (six female and four male; mean age 21.5 years ranging between 19 and 28 years) participated in the experiment. All had normal or corrected to normal vision. Subjects were paid for their participation and were naive to the purpose of the experiment.

3.1.2. *Apparatus and procedure*

The apparatus and procedure were basically the same as in experiment 1. However, the background was removed, and the liquid crystal spectacles were used to provide monocular or binocular vision. The experiment consisted of two blocks of 48 trials (12 times 4 balls); one with monocular vision and one with binocular vision. Five subjects started with monocular, and five subjects started with binocular vision. Subjects were required to catch balls of 4, 6, 8 and 10 cm in diameter. The experiment took about 60 min.

3.1.3. *Dependent variables and data analysis*

The same dependent variables as in experiment 1 were used. For each subject the mean and standard deviation for each condition was calculated for each dependent variable. For one subject, the data for peak closing velocity, and the moment of completion of the catch could not be obtained due to technical failure. On the means and standard deviations a 2(group: monocular first vs. binocular first) × 2(viewing: monocular vs. binocular) × 4(ball size: 4 vs. 6 vs. 8 vs. 10 cm) ANOVA with repeated measures on the last two factors was carried out. For the main effects post-hoc comparisons were conducted with Tukey's HSD test ($p < 0.05$), while for interaction effects means were compared using Scheffé's S method ($p < 0.05$).

3.2. *Results*

3.2.1. *Catching failures*

Fig. 6 shows the mean number of balls (out of 12) that were not caught, specified for ball size and viewing. The ANOVA revealed significant main effects for ball size ($F(1,24) = 15.04$, $p < 0.001$), viewing ($F(1,8) = 14.50$, $p < 0.01$) and interactions of ball size × viewing ($F(3,24) = 6.47$, $p < 0.01$), viewing × group ($F(1,8) = 14.50$, $p < 0.01$), and viewing × ball size × group ($F(3,24) = 8.22$, $p < 0.001$). Post hoc indicated that catching failures occurred most frequently for the 4 cm balls in the monocular viewing condition by the group that started monocular, that is, during the first half of the experiment.

3.2.2. *Temporal characteristics: Effects of ball size and viewing*

Table 3 shows the means and standard deviations of the three temporal variables of the catch. ANOVA revealed for the moment of onset of the catch a significant a main effect for ball size ($F(3,24) = 11.29$, $p < 0.001$), and a significant interaction of ball size × viewing ($F(3,24) = 6.09$, $p < 0.01$). The main effect for viewing reached a 6% significance level, ($F(1,8) = 4.67$,

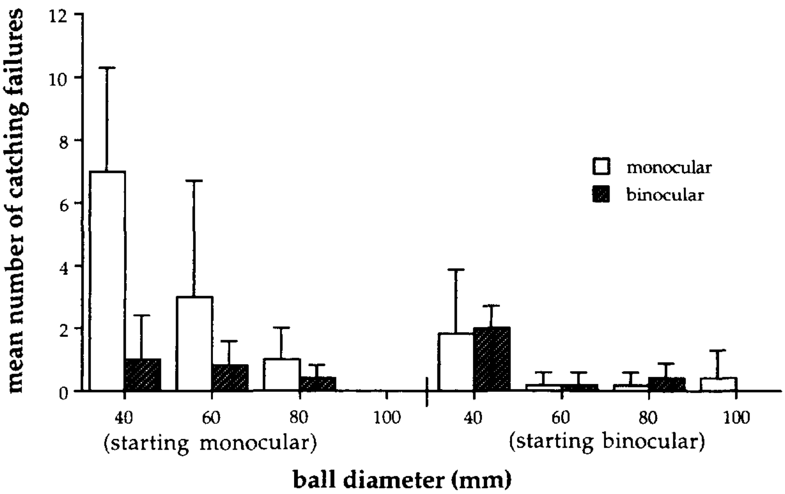

Fig. 6. Number of catching failures for the different balls in the monocular and binocular viewing specified for the two groups of subjects.

$p = 0.06$). Post hoc indicated that in the monocular condition, subjects not only initiated the catch earlier than in the binocular condition, but also earlier for the larger balls as compared to the smaller ones. No differences in timing for the different ball sizes were present in the binocular condition.

For the moment of maximal aperture (i.e., the moment the subjects start to close the hand) only the interaction of viewing × ball size was found significant ($F(3,24) = 4.47$, $p < 0.05$). Post hoc indicated that under monocular vision the hand was closed earlier for the 4 cm ball in comparison to the 10 cm ball. No such differences were present under binocular vision.

The means of the moment of completion of the catch differed significantly for viewing ($F(1,7) = 38.47$, $p < 0.001$), ball size ($F(3,21) = 26.48$, $p < 0.001$) and viewing × ball size ($F(3,21) = 11.30$, $p < 0.001$). Post-hoc analysis indicated that under monocular vision the catch was completed earlier for the larger balls as compared to the smaller ones. No significant differences between ball sizes were present in the binocular condition. Furthermore, significant differences between viewing conditions only existed for the 4 and 6 cm balls.

With respect to the standard deviations, all temporal landmarks showed a main effect for viewing: the moment of initiation of the catch ($F(1,8) = 20.52$, $p < 0.01$), the moment of maximal hand aperture ($F(1,8) = 7.50$, $p < 0.05$), and the moment of catch ($F(1,7) = 17.21$, $p < 0.01$) were significant. Post

Table 3
Means and standard deviations for all kinematic dependent variables (Experiment 2)

Dependent variable	Viewing	Ball size					*F*-value	
		40 mm	60 mm	80 mm	100 mm		Mean	SD
Moment of onset	Monocular	804 (139)	855 (134)	891 (155)	938 (134)	872 (140)	V: 4.67	V: 20.52**
	Binocular	771 (103)	789 (116)	793 (119)	812 (111)	791 (112)	B: 11.29***	B: 0.72
		787 (121)	822 (125)	841 (137)	874 (123)		V × B: 6.09**	V × B: 0.25
Moment of maximal hand aperture	Monocular	254 (142)	306 (135)	320 (131)	329 (119)	302 (132)	V: 2.08	V: 7.50*
	Binocular	274 (122)	288 (101)	258 (99)	239 (68)	265 (98)	B: 1.19	B: 2.50
		264 (132)	397 (118)	289 (114)	284 (94)		V × B: 4.47*	V × B: 0.37
Moment of completion of the catch	Monocular	−109 (69)	−60 (56)	−27 (65)	17 (72)	−44 (65)	V: 38.47***	V: 17.21**
	Binocular	−35 (50)	−16 (55)	−9 (42)	9 (56)	−12 (50)	B: 26.68***	B: 1.02
		−72 (59)	−37 (55)	−18 (54)	13 (64)		V × B: 11.30***	V × B: 1.71
Maximal hand aperture	Monocular	103 (12)	102 (11)	110 (11)	114 (11)	107 (11)	V: 0.17	V: 4.88
	Binocular	96 (11)	98 (9)	111 (8)	120 (9)	106 (9)	B: 28.62***	B: 1.94
		99 (12)	100 (10)	110 (9)	116 (10)		V × B: 15.99***	V × B: 0.25
Peak opening velocity	Monocular	541 (161)	513 (185)	574 (190)	620 (214)	562 (188)	V: 0.53	V: 1.17
	Binocular	495 (185)	463 (133)	566 (170)	604 (189)	531 (169)	B: 10.78***	B: 1.81
		518 (173)	488 (159)	570 (180)	612 (201)		V × B: 1.57***	V × B: 1.19
Peak closing velocity	Monocular	660 (218)	514 (212)	362 (126)	291 (156)	457 (178)	V: 3.16	V: 2.08
	Binocular	519 (193)	452 (152)	399 (168)	239 (92)	403 (151)	B: 35.07***	B: 4.41*
		589 (206)	483 (184)	380 (147)	265 (124)		V × B: 7.00***	V × B: 1.45

Note: Moment of initiation, moment of maximal hand aperture and moment of completion of the catch in milliseconds before ball–hand contact (i.e., minus signs indicate occurrence after contact!). Maximal hand aperture in millimeters, and peak opening and closing velocity in millimeters per second. The *F*-values for the main effects of Viewing (V) and Ball size (B), and the interaction of Viewing × Ball size (V × B) are indicated.
$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

hoc indicated that for all these dependent variables the standard deviation was larger for the monocular viewing condition.

3.2.3. Temporal characteristics: Effects of group

Only for the moment of completion of the catch were effects of group found to be significant. The ANOVA revealed differences for viewing × group ($F(1,7) = 10.78$, $p < 0.05$) and for viewing × ball size × group ($F(3,21) = 4.84$, $p < 0.01$). Post hoc indicated that in contrast to the group that started in the binocular condition, the group that started in the monocular condition completed the catch significantly later during the first part of the experiment as compared to the second part of the experiment. Moreover, for the group that started in the monocular condition, the catch was completed earlier for the larger balls as compared to the smaller balls. The group that started in the binocular condition did not show such pronounced differences; during the first half of the experiment (i.e. under binocular vision) only the smallest ball was caught later than the largest ball (Fig. 7).

With respect to the mean standard deviations, only for the moment of completion of the catch was an interaction of viewing × group found significant ($F(1,7) = 6.96$, $p < 0.05$). Post hoc indicated that the standard deviations only decreased from the first to the second part of the experiment for the subjects who started monocular.

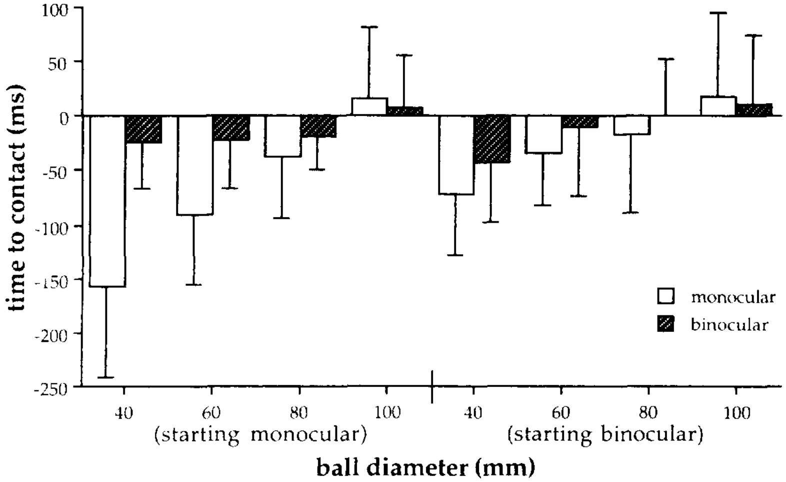

Fig. 7. Moment of completion of the catch for the different balls in the monocular and binocular viewing specified for the two groups of subjects.

3.2.4. Hand aperture, peak opening and closing velocity

Table 3 also reports the means and standard deviations for the dependent variables, maximal hand aperture, peak opening and closing velocity. ANOVA showed that the maximal hand aperture significantly differed for ball size ($F(3,24) = 28.62$, $p < 0.001$) and viewing × ball size ($F(3,24) = 15.99$, $p < 0.001$). Post hoc indicated that maximal aperture increased with ball size. However, this increase was more pronounced in the binocular condition. That is, the hand aperture for the 4 cm ball is larger in the monocular condition, in contrast to the 10 cm ball where the hand aperture is larger in the binocular condition. The mean standard deviations were not found to be significant.

For the means of peak opening velocity a significant effect was found for ball size ($F(3,24) = 10.78$, $p < 0.001$). That is, for the two smallest balls the peak opening velocity was significantly lower than for the largest ball, and also the difference between the 6 and 8 cm balls was found significant. Significant effects for the peak closing velocity were revealed for ball size ($F(3,21) = 35.07$, $p < 0.001$) and viewing × ball size ($F(3,21) = 7.00$, $p < 0.01$). Post hoc indicated for the monocular condition that all means differed except for the differences between the 8 and 10 cm balls. In the binocular condition, however, only the peak closing velocity of the 10 cm ball was lower in comparison to the other balls. Only for the 4 cm ball was a significant difference between the viewing conditions present. In addition, the interaction of ball size × group was found significant ($F(3,21) = 3.10$, $p < 0.05$). Post hoc indicated that the difference in peak closing velocity between the different ball sizes was more pronounced when the subjects started in the monocular condition.

With respect to the standard deviations only the peak closing velocity showed a significant main effect for ball size ($F(3,21) = 4.41$, $p < 0.05$), indicating that standard deviations were the largest for the 4 cm ball.

3.3. Discussion

The findings show that the subjects' performance under monocular viewing has clearly deteriorated in comparison to binocular viewing. Effects of disparity on interceptive action were earlier reported by Judge and Bradford (1988). However, from their study it is difficult to untangle spatial errors from temporal errors. Here, it is shown that the decline in performance is at least partly due to differences in timing. That is, a size-arrival effect, similar to that found in Experiment 1 and in studies using computer simulated environments, was observed when subjects were looking monocular, resulting in more catching failures. In the binocular condition, however, subjects behaved in accordance with a constant time to contact strategy and did so more accurately. Again, it could be argued that the observed timing patterns are due to physical constraints such as differences in the amount of precision control needed. That is, when difficulty in precision control is a mediating factor, the higher accuracy demands in the case of smaller balls will lead to a lengthening of the movement durations (cf. Marteniuk et al., 1990; Paulignan et al., 1991). To examine this possibility, the total grasp duration, the opening duration and the closing duration were calculated (for details see the discussion in Experiment 1, Section 3.2) and are reported in Table 4. A 2(viewing: monocular vs. binocular) × 4(ball size: 4 vs. 6 vs. 8 vs. 10 cm) ANOVA with repeated measures was carried out. In contrast to the results with respect to the temporal characteristics, no interaction effects for viewing × ball size for movement duration were found, strongly indicating that the observed timing patterns are not simply due to difficulty in precision control. Significant main effects of ball size were revealed for the opening duration ($F(3,27) = 3.40$, $p < 0.05$) and closing duration ($F(3,24) = 6.40$, $p < 0.01$). However, as can be seen from Table 4, the relation between ball size and movement duration is in an opposite direction for the opening duration as compared to the closing duration, and thus no unambiguous interpretation can be given. Interestingly, both the total grasp duration and the closing duration were significantly lengthened in the monocular condition ($F(1,8) = 7.74$, $p < 0.05$, and $F(1,8) = 6.64$, $p < 0.05$, respectively), suggesting a contribution of binocular viewing in precision control independent from object size. In sum, it can be concluded that the temporal characteristics of the grasp phase in catching are primarily dependent on the available information sources, and that the size-arrival effect in the monocular condition is not due to physical constraints, but information based.

It would be illogical to argue from these results that tau (i.e., the inverse of the relative rate of dilation) was used in the binocular condition only. It can be concluded therefore, that it is a binocular information source which results in a constant time to contact strategy. Hence, the conclusion from previous studies (e.g. Lee et al., 1983; Savelsbergh et al., 1992) that (monocular) tau controlled the timing of the act might have been premature, because the subjects in these studies had binocular information sources available. In addition, the size-arrival effects in the monocular condition question the use of tau even when only monocular information sources are available, and hence, an explanation of the control of timing exclusively on basis of tau must be ruled out.

Table 4
Means and standard deviations for the movement durations (Experiment 2)

Movement duration	Viewing	Ball size					*F*-value	
		40 mm	60 mm	80 mm	100 mm		Mean	SD
Total grasp duration	Monocular	946 (148)	947 (142)	951 (166)	942 (138)	947 (148)	V: 7.74*	V: 8.48*
	Binocular	829 (128)	831 (137)	821 (129)	833 (111)	829 (126)	B: 0.09	B: 2.08
		888 (138)	889 (140)	886 (147)	887 (124)		V × B: 1.18	V × B: 0.50
Opening duration	Monocular	576 (157)	548 (147)	572 (162)	602 (155)	575 (155)	V: 0.90	V: 8.92*
	Binocular	497 (152)	500 (124)	541 (119)	602 (108)	535 (126)	B: 3.40*	B: 1.23
		536 (154)	524 (136)	556 (140)	602 (132)		V × B: 1.18	V × B: 1.20
Closing duration	Monocular	364 (148)	364 (120)	347 (119)	301 (112)	344 (125)	V: 6.64*	V: 7.69*
	Binocular	311 (122)	306 (112)	256 (88)	230 (70)	276 (98)	B: 6.40**	B: 2.49
		337 (135)	335 (116)	301 (103)	265 (91)		V × B: 0.64	V × B: 0.47

Note: All durations are in milliseconds. The *F*-values for the main effects of Viewing (V) and Ball size (B), and the interaction of Viewing × Ball size (V × B) are indicated.

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

The findings for the moment of completion of the catch were similar to those of the moment of onset of the catch and the moment of maximal aperture. It should be noted, however, that these differences occurred only in the first part of the experiment for only those subjects who started monocular; the effects disappeared during the second, binocular part of the experiment. In contrast, the subjects who started in the binocular viewing condition seemed to have learned to anticipate the moment of contact more accurately during the first part of the experiment: the effects of viewing and ball size in the monocular viewing condition were diminished (the same was found for the moment of peak closing velocity; $F(3,21) = 11.18$, $p < 0.001$). Thus, as in experiment 1, practice influences the final accuracy in the timing of the grasp, but not the initiation of the opening and closing of the hand. As such a funnel-like control (Bootsma and Van Wieringen, 1990) between trials seems to emerge with practice.

4. General discussion

Recent research with respect to coincidence timing or anticipation is often based on studies using computer displays. However, if perception is specific for action (Gibson, 1979), then generalizing the findings obtained from computer simulated environments to real world interceptive actions such as catching might be hazardous. Not only do the constraints on action differ vastly (cf. Bootsma, 1989), but also the available information is often poor or conflicting (cf. Tresilian, 1994). In catching, subjects can adjust their movements during the act and potentially have different non-conflicting sources of information available. Although researchers have argued that the relative rate of optical expansion is used to control the temporal characteristics of interceptive action (Lee et al., 1983; Savelsbergh et al., 1991, 1993), there is some suggestive evidence that binocular vision and/or environmental structure might enhance performance in the temporal domain (e.g. Judge and Bradford, 1988; Rosengren et al., 1988; Savelsbergh and Whiting, 1988). This paper adds to the present state of affairs.

4.1. *Differences in timing*

In his *Dioptrica Nova* Molyneux (1690) already seemed to have anticipated the main findings of the present experiments. He wrote:

> ...as a conclusion to the whole I shall only add one Experiment that demonstrates we see with both eyes at once; and 'tis, that which is commonly known and practiced in all tennis courts, that the best player in the world hoodwinking one eye shall be beaten by the greatest bungler that ever handled a racket; unless he be used to the trick, and then by custom he gets a habit of using one eye only (pp. 294–295, in Cutting, 1986, 258 pp.).

This conclusion probably exaggerates the influence of binocular vision, but when examining the number of catching failures, it is evident that binocular vision, but not environmental structure, facilitates catching performance. Moreover, after some practice, performance under monocular viewing increases and levels the performance when viewing binocular. The temporal characteristics of the catch, however, demonstrate that under monocular viewing the subjects – particularly in the first part of grasp – continue to behave in contrast with a constant tau-margin strategy. Hence, tau or the relative rate of expansion cannot exclusively explain the timing of the catch. Different sized balls resulted in different moments of opening and closing the hand under monocular viewing conditions, irrespective of the presence of environmental structure: the hand opened and closed sooner the larger the ball, suggesting the involvement of a lower order information source (cf. Michaels and De Vries, 1997) like image size or its derivative. The constant time to contact strategy used under binocular viewing strongly suggests the use of an information source related to disparity that specifies time to contact. In sum, multiple ways of visual control of interceptive timing are discriminated, depending on the available informational constraints. Can one controlling (higher order) mechanism or (higher order) information source be derived, or are multiple information sources involved? Several approaches can be discerned in this respect.

4.1.1. The inferential approach

The most specific predictions have been made by the advocates of the inferential approach. Tresilian (1994) (see also Wann and Rushton, 1995), e.g., proposed a model in which various sources of information, obtained from different sensory systems, are evaluated. In this evaluation process the available information sources are differentially weighted and combined (e.g. summing up and/or multiplying the information sources), resulting in a time to contact estimate. Tresilian (1994) proposed a weighting dependent upon the image size such that 'the larger the image size, the greater the confidence in visual tau' (p. 350). Because there are less competing information sources in the monocular viewing condition without background, tau will be the most important information source and, consequently, differences in timing for different object sizes are expected to be minimal under these informational constraints. Since the present findings do not support this hypothesis, the least one can say is that a different evaluation principle is needed. Nevertheless, the model is attractive because it can accommodate the use of different information sources within one action.

A second inferential explanation is that of Smeets and Brenner (e.g. Smeets and Brenner, 1995b; Smeets et al., 1996). These authors argue that the time to contact is calculated from perceived distance and velocity, which are perceived independently. Systematic errors in either perceived distance or perceived velocity lead to misjudgements of time to contact. Experimental evidence for this proposition mainly stems from experiments with laterally moving objects. Smeets et al. (1996), for instance, used a moving background to induce changes in the perceived velocities of laterally moving objects. It was shown that background motion led to systematic errors in subjects' time to contact judgements.

Inspection of the maximal hand aperture of the subjects in the present experiments (Tables 1 and 3) shows a relative underestimation of ball size for the larger balls in comparison to the smaller balls, the relative underestimation being more pronounced in the monocular condition. Following the size–distance invariance (Kilpatrick and Ittelson, 1953), it can be argued that this underestimation of perceived size is related to an underestimation of perceived distance. Provided that perceived velocity is not effected, this underestimation of perceived distance results in an underestimation of time to contact judgements and may lead to a size-arrival effect as observed in the present experiments as well as in visually guided ones reaching to stationary targets (Servos et al., 1992). However, two objections can be raised to this explanation. The first one is that it holds in its pure form only when perceived velocity is not affected by object size, even when viewed monocular. Brenner et al. (1996) demonstrated that for head-on approaches, velocity can be estimated from optical expansion. But, to obtain velocity, optical expansion should be scaled in terms of distance or size of the object (Brenner et al., 1996; Tresilian, 1990, 1991). As a consequence, underestimation of object size leads not only to an underestimation of distance, but also to an underestimation of perceived velocity. Theoretically, these underestimations may cancel out and, consequently, do not have to lead to different time to contact judgements for different objects. If, however, the distance or size information used for scaling the perception of velocity depends on information sources different from that used in perceiving distance (e.g. accommodation, motion parallax), the model may indeed incorporate the present results.

The second objection to this explanation is related to the assumption regarding the size–distance invariance. That is, empirical evidence for the mapping between the geometrical size–distance relation and the perception of size and distance is not unequivocal and some authors even concluded that a size–distance paradox could exist. That is, an underestimation of perceived size is related to an *over*estimation of perceived distance (Kilpatrick and Ittelson, 1953; Epstein et al., 1961; Sedgwick, 1986).

A more general and theoretical objection is the inferential nature of both models themselves. In other words, the required action is calculated/evaluated from discernible perceptions, implying an intelligent 'thing' or 'being' doing the evaluation or calculation.

4.1.2. A direct perception explanation

The second viewpoint is that of direct perception (Gibson, 1979). From this perspective, the perception of a dynamical event entails the detection of a single or collective informational variable specifying the event (cf. Michaels and De Vries, 1997). The present experiments show that, with respect to the grasp phase in catching, the single informational invariant is not tau. Thus, following the strong interpretation of direct perception, this single (collective or higher order) informational invariant has not been identified as yet. However, when an actor uses different perceptual strategies, such as those demonstrated in the present experiments, it may be difficult if not impossible to find such a single (collective) invariant. That is, this single (collective or higher order) invariant should be binocular in nature but, nevertheless, be capable of incorporating systematic variances from this binocular 'baseline' when only monocular vision is available. In this case, it might be more fruitful to argue that multiple information sources, which are still specific, specify the same dynamical event as is argued by proponents of the directed perception approach.

4.1.3. Directed perception

Proponents of the directed perception approach (Cutting, 1986; Laurent et al., 1995, 1996) argue that the perceptual system selects the appropriate informational invariant depending on the task constraints at hand. That is, different information sources can be used under different informational constraints. In case of monocular viewing the timing might be controlled on the basis of the tau-function of the visual angle, whereas in case of binocular vision the tau-function of disparity (Laurent et al., 1995, 1996) may be the more likely candidate. The tau-function is defined as the relation between an optical variable and its first derivative (Lee et al., 1991). Thus, the monocular tau definition as used throughout this paper is equivalent to the tau-function of the visual angle. Notice that in most studies involving interceptive timing, which sought to provide evidence for the role of tau-function of the visual angle, also binocular vision and therefore the tau-function of disparity was present (e.g. Lee and Reddish, 1981; Lee et al., 1983, 1991; Peper et al., 1994; Savelsbergh et al., 1992; Sidaway et al., 1989).

Since under monocular viewing ball size did influence interceptive timing, an information source different from the tau-function of visual angle must be involved. Although it does not specify time to contact, this information source may be a lower order information source such as image size or image velocity. The fact that in the monocular condition subjects did use a perceptual strategy that, depending on ball size, systematically deviated from a constant time to contact strategy points in this direction. In other words, although it is not specific to the *perception* of time to contact, lower order information sources may, depending on the task constraints, be specific in the control of interceptive *action*.

4.2. Effects of practice

The discussion so far has mainly focused on the onset of the grasping phase of the catch. However, as shortly mentioned above, in the monocular conditions, learning effects occurred during the course of the experiments for the moment of maximal hand aperture and the moment of completion of the catch. In contrast to studies in time to contact perception, the size-arrival effect weakened or even completely disappeared. These contrasting findings may shed some light on the contribution of different information sources in the visual control of interceptive action under monocular viewing. In studies using computer displays, for instance, vision of the approaching target is necessarily 'occluded' in the last few 100 ms, making extrapolations from memory necessary for judging time to contact. In other words, in these studies time to contact judgements are based on information from the earlier parts of the trajectory of the approaching objects. This may emphasize the emergence of the size-arrival effects. Moreover, the nature of a short ballistic button press task leaves no room for adjustments during the act, and learning thus is virtually impossible when no knowledge of results is presented. In natural interceptive actions, however, continuous adjustments guided by visual information can be made until the end of the act minus the visual motor delay, which is about 100 ms (Lee et al., 1983; Bootsma and Van Wieringen, 1990; Smeets and Brenner, 1995a).

One may wonder about the nature of the monocular information used during the final ‘homing in’ into the ball. One explanation for the weakening or disappearance of the size-arrival effect for the completion of the catch is that subjects shift from optical to haptical information; subjects close their hand rapidly when the ball hits the hand. However, the latencies (in most conditions less than 50 ms, see Tables 1 and 3) are shorter than the required physiological conduction times. This is not say, however, that tactile or haptical information is not used at all. Moreover, actually grasping a ball might provide haptical information specifying the size of the balls (e.g. Chan and Carello, 1988), and familiar or known size has been shown to influence monocular based time to contact judgements (Stewart et al., 1993). The artificial momentum at the moment of ball–hand contact, due to the ball stopping at the hand, may be another parameter influencing the occurrence of the practice effects for the moment of completion of the catch. Lacquanti and Maioli (1989) demonstrated that the haptic control of this momentum between the ball and hand is an important determinant for successful performance in catching. Therefore, it necessarily remains ambiguous as to what extent the disappearance of the ‘late catching error’ is exclusively due to improvements in anticipatory timing or whether the haptic control of the momentum between the ball and hand is a mediating factor.

Nevertheless, subjects learned to anticipate arrival of the ball under monocular viewing. Therefore, tau as an information source for the final hand adjustments is still a likely candidate. There are two observations that support this contention. Apart from the observed learning from a non-constant to a constant time to contact strategy in this experiment, there is another observation which supports a role for tau for the final homing in on the ball. The effect of manipulating tau (i.e. deflating the ball) in Savelsbergh et al. (1991) was most pronounced at the moment of peak closing velocity of the hand, that is, just before contact. Therefore, subjects in the monocular conditions may have started the catch on the basis of some lower order information source like image size, and started their final hand adjustments only a few 100 ms before contact using tau. Such a change from one information source (at the onset of the catch) to another information source (at or just after the moment of maximal aperture) might be easier to reconcile with the inferential model of Tresilian than with a directed perception approach. The weighting of different available information sources changes during the flight of the ball because image size changes during approach. This weighting changes with practice. Nevertheless, from a directed perception approach, it can be argued that with practice subjects become attuned to, or select, tau in the final part of the catch. That is, in the course of the experiment the use of tau is strengthened by the number of catching failures and/or the tactile information about the ball size. For such a hypothesis to be meaningful, however, the concepts of attainment and selection clearly need further elaboration (e.g. Edelman, 1987; Thelen and Smith, 1994).

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