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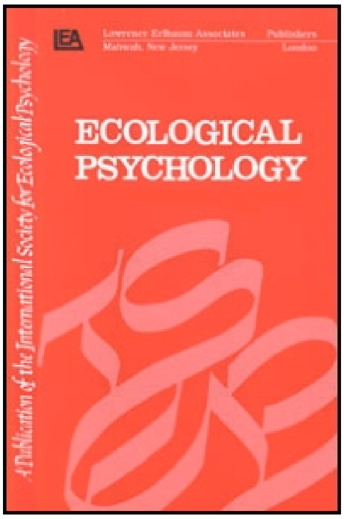

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A Comparison of Real Catching With Catching Using Stereoscopic Visual Displays

Joost C. Dessing, C. (Lieke) E. Peper, and Peter J. Beek
Institute for Fundamental and Clinical Human Movement Sciences
and Faculty of Human Movement Sciences
Vrije Universiteit
Amsterdam, The Netherlands

To date, the usefulness of stereoscopic visual displays in research on manual interceptive actions has never been examined. In this study, we compared the catching movements of 8 right-handed participants (6 men, 2 women) in a real environment (with suspended balls swinging past the participant, requiring lateral hand movements for interception) with those in a situation in which similar virtual ball trajectories were displayed stereoscopically in a virtual reality system (Cave Automated Virtual Environment [CAVE]; Cruz-Neira, Sandin, DeFranti, Kenyon, & Hart, 1992) with the head fixated. Catching the virtual ball involved grasping a lightweight ball attached to the palm of the hand. The results showed that, compared to real catching, hand movements in the CAVE were (a) initiated later, (b) less accurate, (c) smoother, and (d) aimed more directly at the interception point. Although the latter 3 observations might be attributable to the delayed movement initiation observed in the CAVE, this delayed initiation might have resulted from the use of visual displays. This suggests that stereoscopic visual displays such as present in many virtual reality systems should be used circumspectly in the experimental study of catching and should be used only to address research questions requiring no detailed analysis of the information-based online control of the catching movements.

The perceptual guidance of actions has been a topic of research for decades. In examining how actions are guided by various information sources, it is important

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Requests for reprints should be sent to Joost C. Dessing, Faculty of Human Movement Sciences, Vrije Universiteit, Van der Boechorststraat 9, 1081 BT, Amsterdam, The Netherlands. E-mail: joost.dessing@fbw.vu.nl

to control and manipulate candidate informational variables in dedicated experiments (e.g., Duchon & Warren, 2002; Savelsbergh, Whiting, & Bootsma, 1991; Smeets & Brenner, 1995; Van Santvoord & Beek, 1994). Because in many cases rather complicated setups are required to manipulate the perceptual variables of interest, virtual reality (VR) may provide a promising alternative because it provides a means to precisely control optical information in an experiment. Indeed, given the current technology, VR can and has been used to study the performance of several tasks (Tarr & Warren, 2003), including navigation (Duchon & Warren, 2002; Kearns, Warren, Duchon, & Tarr, 2002), crawling (Withagen & Michaels, 2002), and reaching (Bingham, Bradley, Bailey, & Vinner, 2001). For tasks involving medium-speed movements, the 50 to 120 msec movement-optics delay of VR systems (depending on the specifications of the hardware and the complexity of the virtual scene; see also Zaal & Michaels, 2003) may not have serious drawbacks. However, for the study of manual interceptive actions in VR, even small movement-optics delays may be expected to have a detrimental influence considering the relatively short time scale at which these actions unfold combined with their delicate timing requirements. Besides the fact that virtual balls cannot be actually intercepted (see Zaal & Michaels, 2003), this may explain why VR has seldom been used in studies of the perceptual guidance of interceptive actions.

Another potentially important drawback of VR systems in studying interceptive actions pertains to the fact that, when constructing a three-dimensional visual space from dual two-dimensional displays, accommodation must be maintained on the fixed two-dimensional images, whereas disparity may require vergence eye movements (cf. Wann, Rushton, & Mon-Williams, 1995). Thus, only if the fixation distance (i.e., the magnitude of accommodation required for sharp vision) can be adjusted in real time to comply with such vergence eye movements would the perceptual consequences of a particular visual scene in VR be identical to those in the real world.[1] This problem amplifies with the difference between the fixation distance and the distance to the virtual visual target as well as with the extent to which this target moves toward or away from the observer (or vice versa). Both factors arise in conjunction in the task of intercepting a fly ball (Zaal & Michaels, 2003), whereas the problem of a changing observer–object distance (i.e., a continuously changing vergence distance with a constant fixation distance) is most prominent in manually catching virtual objects approaching from a relatively small distance (i.e., in virtual equivalents of the tasks studied by Montagne, Laurent, Durey, & Bootsma, 1999; Peper, Bootsma, Mestre, & Bakker, 1994). Because it is impossible to predict when the accommodation-vergence limitation of VR will be resolved (if ever), it is important to examine the effects of the use of stereoscopic visual displays, such as used in most VR systems, on catching behavior to evaluate

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[1] It is interesting to note here that Bingham et al. (2001) actually used this shortcoming of VR as a manipulation of accommodation to study egocentric distance perception in reaching.

the usefulness of current VR setups in this regard for investigations of (the effects of perceptual manipulations on) catching.

For stereoscopic visual displays of virtual ball trajectories to be meaningfully (i.e., validly) used to study catching, it is required that the "virtual" catching of a stereoscopically displayed ball sufficiently resembles that of real balls. To determine whether this is in fact the case or not, an experiment was performed in which participants performed ("normal") catching and simulated catching movements in response to a variety of real and virtual ball trajectories (requiring hand movements in lateral direction) while accurate recordings were being made of those movements. In the experiment in question, the potential problem caused by the movement-optics delay of the VR system was avoided by eliminating the updating of the visual images on the basis of movements of the observation point and constraining the head movements with a chin rest. As a consequence, the experiment allowed for a "clean" evaluation of the use of stereoscopic visual displays to manipulate ball trajectories in catching research rather than an evaluation of the influence of the movement-optics delay as has been a main concern in most previous studies on the use of VR systems in the study of perception and action.

METHODS

Participants

All eight right-handed (Oldfield, 1971) participants (6 men, 2 women, M age = 23.5 years, range = 20–29 years) reported normal or corrected-to-normal stereoscopic vision (stereoacuity > 60 sec arc^{-1}; Titmus Optical, Inc., Petersberg, VA). They gave their informed consent before participating in the experiments and were paid an hourly fee for their participation.

Experimental Setups

Three experimental setups were created, referred to as the Catching experiment, the Grasping experiment, and the CAVE experiment (involving "catching" in a Cave Automated Virtual Environment; Cruz-Neira, Sandin, DeFranti, Kenyon, & Hart, 1992). In the Catching experiment, the participants actually intercepted the approaching balls passing them on the right hand side, whereas in the Grasping experiment they were instructed to grasp a handheld lightweight ball that was attached to the palm of the hand at the moment and at the position at which they would have caught the approaching ball (whose flight was, however, blocked just prior to the moment of "interception"). In the experiment in the CAVE—a 3.05 × 3.05 × 3.05 m room whose floor, front, and sidewalls consists of (rear-)projection screens—the participants performed the same (i.e., grasping) task but now in response to virtual (i.e., projected) rather than real ball trajectories. (The Grasping experiment served as a control for the CAVE experiment in that it allowed for an evaluation of the effect of eliminating actual ball contact on catching performance.)

During all experiments, participants were seated comfortably in a chair. To minimize head movements, the head was fixated in a chin rest that allowed for rotations around a vertical axis.[2] Average eyeheight was 130.5 cm. The right hand could be moved in a lateral direction along a horizontal bar positioned 28.5 cm below and 13.0 cm in front of the eye. White balls (diameter = 8.0 cm; mass = 0.146 kg) were presented against a black background. Two initial ball positions (IBPs; 3.8 cm to the left and 83.8 cm to the right of the cyclopean eye) and three interception points (IPs; 20.0, 40.0, and 60.0 cm to the right of the cyclopean eye) were used, resulting in six ball trajectories (see Figure 1). The IPs were defined 21.5 cm below and 20.0 cm in front of the eyes corresponding to the average position where the ball was caught. The participant started a trial with his or her hand positioned at one of three initial lateral hand positions (IHPs; 20.0, 40.0, and 60.0 cm to the right of the cyclopean eye).

In the Catching and Grasping experiments, balls were suspended from the ceiling (at a height of 6.11 m) using plastic coated steal wires (length = 5.25 m, diameter = 0.6 mm). Prior to release, the balls were pulled up and back to the IBPs at a height of 5.10 m, 6.99 m in front of the participant's eyes. The balls could be released automatically from these positions using computer-controlled switches (cf. Peper et al., 1994). Visibility of the approaching ball was controlled by switching the liquid crystal (LC) glasses (PLATO System P–1, Translucent Technologies, Toronto, Ontario, Canada) from opaque to transparent and vice versa. The balls became visible 0.4 to 0.6 sec after ball release (the exact moment was randomized) and invisible 60 msec before the ball reached the IP. In the Grasping experiment, a white foam ball (diameter = 8.0 cm, mass = 0.006 kg) was attached to the palm of the hand. An Optotrak camera system (Northern Digital, Inc., Waterloo, Ontario, Canada), positioned 2.5 m to the left of the participant at 2 m height registered the position (at 200 Hz) of infrared emitting diodes (IREDs) on the lateral side of the tip of the index finger, on the thumb nail, and the back of the hand. The hand marker was attached to the left side of a 5 cm long foam rod placed 5 cm proximal to the distal end of the metacarpal bone III to prevent the marker from becoming invisible for the Optotrak sensors. The Optotrak recordings were triggered at the moment of ball release.

To calculate the images to be projected in the CAVE, the ball trajectories as presented in the Catching and Grasping experiments were simulated in the software program MatLab (The MathWorks, Inc., Natick, MA), as the pendular motion of a suspended point mass. Given ball mass, wire length, initial and final ball position, and flight times measured during the Catching and Grasping experiments

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[2] Given the limited accuracy of the images presented in the CAVE, small head rotations in the horizontal plane were allowed, and eye position was calibrated at a neutral head position.

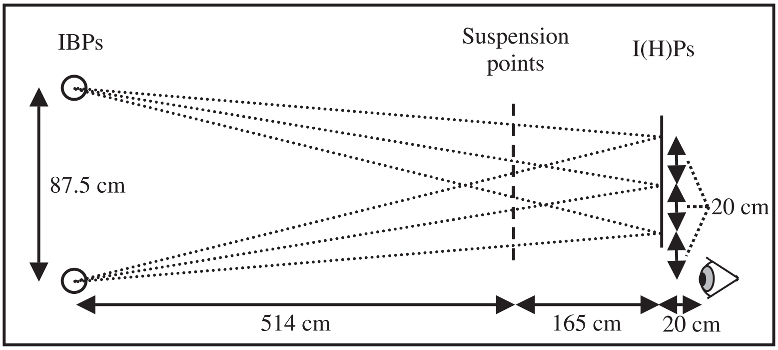

FIGURE 1 Schematic presentation of the ball trajectories (viewed from above). IP, IBP, and IHP refer to interception point, initial ball position and initial hand position, respectively.

(average flight time = 1.56 sec), the air friction coefficient k was calculated (k = 0.0684 kg/m; air friction was defined as $-kv^2$, where v is the ball's tangential velocity). Screen images (1,280 × 1,024 pixels) were generated at 120 Hz; a stereoscopic effect was induced by synchronizing the opening and closing of the left and right CrystalEyes LC glasses (StereoGraphics Co., San Rafael, CA) with the images presented on the screen, which alternated between images for the left and right eye (at 60 Hz each). The images presented in the CAVE were not updated on the basis of movements of the observation point (which were instead minimized by using a chin rest); the cyclopean eye position was predefined in the CAVE software. The eyes were positioned at a distance of approximately 2.45 m from the front screen. Visibility of the ball was controlled by starting (0.4–0.6 sec after ball release) or stopping (60 msec before the ball reached the IP) the projection of the ball's image.

Also in the CAVE, the hand and finger movements were registered using Optotrak. To avoid interference between the Optotrak IRED signals and the IRED signals used to control the LC goggles in the CAVE, the markers had to be pointing forward.[3] As a result, the Optotrak camera had to be positioned 2 m in front of the participant on the floor of the CAVE[4] while the markers were placed on the palmar side of the index finger and thumb and on the front side of the lightweight ball that was attached to the palm of the hand (the same ball as used in the Grasping experiment). The Optotrak recordings in the CAVE were triggered by an optical sensor, which was placed against the right screen at the position where (outside of the participant's field of view) a white square appeared at the moment of virtual ball release.

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[3] An IRED marker pointing in the direction of the goggles resulted in a distorted "opening" and "closing."

[4] Although Northern Digital prescribes a minimal camera distance of 2.2 m, movements could be recorded accurately.

Procedure

After each trial in the Catching and Grasping experiments, the ball was manually transported back to its IBP, whereas in the CAVE experiment, simply a new simulated ball trajectory was selected. In all three experiments, the participants moved their hand to the required IHP guided by instructions of the experimenter. The ball started to move 0.2 to 0.5 sec (randomly selected) after the experimenter pressed a key on the keyboard. Participants were instructed to move to the IP with their hand opened and, depending on the experiment, to either catch the ball (in the Catching experiment) or to grasp the foam ball attached to the palm of their hand as if they were catching the approaching (simulated) ball (in the Grasping and CAVE experiments). In the Grasping experiment, this required blocking the ball's motion (40 msec before the ball reached the IP, thus, after the ball became invisible; see previously).

In each experiment, the 18 conditions (i.e., 3 IPs × 2 IBPs × 3 IHPs) were repeated three times; the resulting 54 trials were presented in a random order. The order of the Catching and Grasping experiments was counterbalanced over participants; the CAVE experiment was performed after the other experiments were completed. Running the Catching and Grasping experiments took about 2 hr for each experiment due to the time needed to transport the balls back to their IBPs, whereas running the CAVE experiment only took about 45 min.

Data Reduction

For the Catching experiment, both successful (i.e., trials in which the ball was caught; $n = 405$) and unsuccessful ($n = 27$) trials were included in the analysis. If, for a given trial, the number of consecutive missing values in the kinematic data of a certain IRED marker did not exceed 12, these values were interpolated using a cubic spline, and the data were low-pass filtered using a recursive fourth-order Butterworth filter (cutoff frequency = 10 Hz). Otherwise, the marker was excluded from further analysis. As a result, the grasp parameters of 5 of the 8 participants could not be determined for the CAVE experiment, which led to the exclusion of the CAVE experiment from the statistical analyses of the grasp parameters. This analysis (applied to the data of the Catching and Grasping experiments) involved only 7 participants because for 1 participant the grasp parameters could not be determined for any of the experiments. The hand movement parameters could be determined for all participants and for all experiments (although 7 trials had to be excluded).

To analyze the grasping movement, peak aperture (PA), peak closing velocity (PCV), moment of grasp initiation (T_{Gini}), and moment of PCV (T_{PCV}) were determined. PA and PCV were defined as the maximal distance between the markers on the thumb and index finger and its maximal absolute rate of change, respectively. T_{Gini} was defined as the moment of the last zero crossing of the closing velocity before T_{PCV}, which did not necessarily correspond to the moment of PA. Both T_{Gini} and T_{PCV} were defined relative to the moment the ball reached the IP. To analyze the timing and accuracy of the lateral hand movement, the moment of movement initiation ($T_{initiation}$), the constant error of final hand position (CE_{FHP}), and the absolute error of final hand position (AE_{FHP}) were determined. $T_{initiation}$ was defined as the moment (relative to the moment the ball reached the IP) of the last zero crossing of the lateral hand velocity before its absolute value exceeded 0.1 m/sec. CE_{FHP} was defined as the lateral hand position at the moment the ball passed the IP relative to the IP. (Note that a nonzero CE_{FHP} does not necessarily indicate an error in performance: Dependent on hand orientation, balls could be caught while the marker on the hand was not precisely at the IP.) AE_{FHP} was defined as the absolute value of CE_{FHP} and thus represents the distance between the hand and the defined IP at the moment the ball passed this IP.

The dependent variables mentioned so far were selected because they are widely used in experimental studies of catching and grasping. However, because recent empirical and theoretical studies of interceptive actions (cf. Dessing, Bullock, Peper, & Beek, 2002; Jacobs, 2001; Montagne et al., 1999) have focused on systematic changes in movement direction, the path length of direction reversals (Δ_{LHP}) and the number of movement reversals (MRs) were calculated as well so that it could be examined whether stereoscopic visual displays may be meaningfully used in experiments addressing directional changes in catching trajectories. Δ_{LHP} indicates how directly movements were aimed at the final hand position and was defined as the total path length of the movement made between $T_{initiation}$ and the moment the ball passed the IP minus the net distance that was covered in this period. If $\Delta_{LHP} > 0$, direction reversals were present during the trial. Such direction reversals were considered MRs if they were preceded and followed by a significant velocity peak. To consider such kinematic "irregularities" in more detail, the smoothness of the hand movements was determined. Smoothness was quantified as the integral of the absolute jerk (i.e., the time derivative of acceleration) of the lateral hand movement with respect to normalized time ($NintJerk_{abs}$); the normalization corrects for differences in $NintJerk_{abs}$ due to differences in the integration interval. To examine the smoothness in more detail at the level of the velocity profiles, the number of peaks in the velocity signal was determined. A velocity peak was defined as a significant rise followed by a significant fall in the absolute lateral velocity occurring after $T_{initiation}$, irrespective of the number of actual velocity peaks between this rise and fall. A rise or fall was considered significant if it was larger than at least one of the criterion values (either 0.1 m/sec or 10% of the maximal absolute lateral hand velocity during the trial). The final velocity peak was also selected if at least 50% of its rise time occurred before the ball passed the IP.

Statistical Analyses

For all but two dependent variables, a repeated measures analysis of variance (ANOVA) was conducted using the SPSS software package, with within-subject factors Experiment (3 (or 2) levels), IP (3 levels), IBP (2 levels), and IHP (3 levels) accompanied by paired-samples *t* tests for post hoc analysis. Significant main effects obtained for Δ_{LHP} and $\mathrm{NintJerk}_{\mathrm{abs}}$ were examined further in terms of the number of MRs and the number of velocity peaks, respectively, using a Friedman ANOVA, with subsequent Walsh tests for post hoc analysis (cf. Siegel, 1956). In all cases, a significance level of $p < .05$ was adopted. Data are presented in the text as "mean(standard deviation)."

RESULTS

Grasp Parameters

The selected grasp parameters captured the main kinematic characteristics of the grasp profiles. Table 1 shows the significant *F* values for the repeated measures ANOVAs performed on the grasp parameters. As can be seen, there were no significant main effects of the factors Experiment (i.e., Catching vs. Grasping), IBP, and IHP (which are therefore omitted from the table) and only a single significant main effect of IP (i.e., on T_{PCV}), indicating that the overall characteristics of the grasp profiles were hardly affected by the experimental factors as such. However, a number of significant interaction effects occurred, several of which involved the factor Experiment. All significant effects as reported in Table 1 are discussed in detail.

PA. Figure 2 illustrates all the variations (i.e., the interindividual means) of PA over the different experiments, IPs, and IBPs. Post hoc analyses of the significant Experiment × IP interaction on PA showed that, in the Catching experiment, PA was significantly larger for balls passing at IP(1) than at IP(2), whereas in the Grasping experiment, PA did not vary significantly over the IPs. The significant Experiment × IBP interaction occurred because, in the Catching experiment, PA was significantly larger for balls moving outward (i.e., approaching from IBP(1)) than for balls moving inward (i.e., approaching from IBP(2)), whereas in the Grasping experiment, such a significant difference was absent. Finally, the post hoc analyses of the Experiment × IP × IBP interaction revealed that this pattern was only present for the two leftmost IPs (i.e., IP(1&2)), whereas the Experiment × IP interaction was present for both IBPs.

PCV. Despite the significant Experiment × IHP interaction found for PCV, the post hoc comparisons did not show any significant differences: For IHP(1–3), respectively, Catching experiment: 1.18(0.25) m/sec, 1.16(0.22)

TABLE 1
F Values for the Significant Effects Obtained for the Grasp Parameters

	PA	*PCV*	T_{Gini}	T_{PCV}
IP			$F(2, 12) = 3.984^{*}$	$F(2, 12) = 4.809^{*}$
IHP			$F(2, 12) = 5.080^{*}$	
Exp × IP	$F(2, 12) = 7.415^{**}$			
Exp × IBP	$F(1, 6) = 9.993^{*}$			
Exp × IHP		$F(2, 12) = 4.562^{*}$		
Exp × IP × IBP	$F(2, 12) = 5.933^{*}$			

Note. PA = peak aperture; PCV = peak closing velocity; T_{Gini} = time of grasp initiation; T_{PCV} = time of peak closing velocity; IP = interception point; IHP = initial hand position; Exp = experiment; IBP = initial ball position.
$^{*}p < .05$. $^{**}p < .01$.

m/sec, and 1.12(0.25) m/sec; Grasping experiment: 1.12(0.18) m/sec, 1.06(0.12) m/sec, and 1.12(0.16) m/sec. In the Catching experiment, PCV tended to be higher for the leftmost than for the rightmost IHP (i.e., IHP(1) and IHP(3), respectively; $p = .068$).

T_{Gini}. The main effect of IP occurred because T_{Gini} tended to occur earlier the further the IP was located from the head (–116(30) msec, –99(21) msec, and –95(16) msec for IP(1–3), respectively), but the post hoc comparisons showed no significant differences. Post hoc comparisons for the main effect of IHP showed that T_{Gini} occurred significantly later for IHP(1) (–89(16) msec) compared to IHP(3) (–109(25) msec; IHP(2): –112(25) msec).

T_{PCV}. Post hoc analyses of the main effect of IP revealed no significant differences, but PCV tended to occur later the further to the right the IP was located (–47(25) msec, –29(12) msec, and –24(6) msec, for IP(1–3), respectively).

Hand Movement Parameters

Table 2 shows the significant *F* values for the repeated measures ANOVAs on the hand movement parameters. As can be seen, there were many main and interaction effects involving the factor Experiment. Figure 3 shows representative kinematics of a single subject for one condition in the three experiments: The profiles illustrate essential systematic differences between the experiments such as differences in initiation time and smoothness of movement. The significant effects as reported in Table 2 are discussed in detail.

$T_{initiation}$. $T_{initiation}$ specifies when the hand movement was initiated relative to the moment the ball passed the IP and thus constitutes an index of the effective movement time. Hand movements were initiated significantly later in the

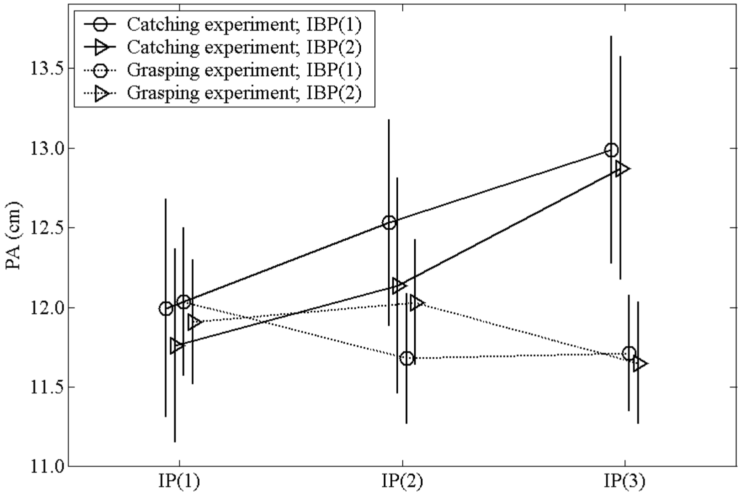

FIGURE 2 Mean values of peak aperture (PA; averaged over participants) as a function of interception point (IP) presented for each initial ball position (IBP) and for the Catching and Grasping experiments separately. Error bars indicate standard errors. The numbers 1 through 3 (IP) and 1 to 2 (IBP) refer to the lateral position (1 = closest to the participant).

CAVE (–543(172) msec) than in the Catching (–690(161) msec) and Grasping (–645(201) msec) experiments, resulting in the significant main effect of Experiment. The significant main effect of IP occurred because hand movements were initiated later the further to the right the ball passed the participant (–758(175) msec, –648(172) msec, and –472(153) msec for IP(1–3), respectively; all post hoc comparisons significant). The significant main effect of IBP showed that hand movements were initiated later for balls moving inward (i.e., approaching from IBP(2); –590(164) msec) than for balls moving outward (i.e., approaching from IBP(1); –662(164) msec). The main effect of IHP was caused by the fact that hand movements were initiated later if the hand started further to the right (–655(168) msec, –629(165) msec, and –593(160) msec for IHP(1–3), respectively; all post hoc comparisons significant).

Post hoc analyses of the IP × IBP interaction showed that, for both IBPs, $T_{\text{initiation}}$ varied not only over the three IPs but also over the two IBPs associated with each IP (IBP(1): –787(176) msec, –669(169) msec, and –529(157) msec for IP(1–3), respectively; IBP(2): –729(174) msec, –627(179) msec, and –415(153) msec for IP(1–3), respectively). Probably, the interaction effect was caused by the larger difference between $T_{\text{initiation}}$ between the rightmost IPs (i.e., IP(2) and IP(3)) for balls approaching from IBP(2) than for balls approaching from IBP(1).

The significant IBP × IHP interaction showed that, for both IBPs, hand movements were initiated later the further to the right the hand was positioned initially. For balls approaching from IBP(1), this was expressed by a significantly

TABLE 2
F Values for the Significant Effects Obtained for the Hand Movement Parameters

	$T_{initiation}$	CE_{FHP}	AE_{FHP}	$NintJerk_{abs}$	Δ_{LHP}
Exp	$F(2, 14) = 5.901$*		$F(2, 14) = 23.894$***	$F(2, 14) = 15.675$***	$F(2, 14) = 5.128$*
IP	$F(2, 14) = 97.290$***	$F(2, 14) = 4.486$*	$F(2, 14) = 7.943$**		$F(2, 14) = 9.337$***
IBP	$F(1, 7) = 55.709$***				$F(1, 7) = 10.960$*
IHP	$F(2, 14) = 23.927$***			$F(2, 14) = 16.722$***	$F(2, 14) = 16.747$***
IP × IBP	$F(2, 14) = 7.140$***				$F(2, 14) = 3.973$*
IP × IHP		$F(4, 28) = 5.163$***			$F(4, 28) = 17.506$***
IBP × IHP	$F(2, 14) = 4.422$*			$F(2, 14) = 33.331$***	$F(2, 14) = 6.749$**
Exp × IP × IBP					$F(4, 28) = 2.806$*
Exp × IP × IHP					$F(8, 56) = 2.376$*

Note. $T_{initiation}$ = time of movement initiation; CE_{FHP} = constant error of final hand position; AE_{FHP} = absolute error of final hand position; $NintJerk_{abs}$ = integral of the absolute jerk; Δ_{LHP} = path length of direction reversals; Exp = experiment; IP = interception point; IBP = initial ball position; IHP = initial hand position.

*$p < .05$. **$p < .01$. ***$p < .005$.

earlier initiation from IHP(1) (–689(172) msec) than from IHP(2&3) (–656(162) msec and –641(162) msec, respectively), and for balls approaching from IBP(2) by a significantly later initiation from the rightmost IHP (i.e., IHP(3): –546(158) msec) than from IHP(1&2) (–622(164) msec and –604(172) msec, respectively). For all IHPs, initiation occurred earlier for balls approaching from IBP(1) than for balls approaching from IBP(2).

CE_{FHP}. CE_{FHP} provides an index of any systematic error or bias in the hand position at interception measured relative to the defined location of the IP. Post hoc analyses of the main effect of IP for CE_{FHP} showed that the hand position at interception tended to be more to the left for the rightmost IP than for the other IPs (1.9(2.5) cm, 0.8(2.2) cm, and –0.8(2.0) cm for IP(1–3), respectively; $p = .061$ and $p = .063$, respectively). The IP × IHP interaction revealed that movements starting at the leftmost IHP (i.e., IHP(1)) ended up significantly more to the left of IP(3) (–1.9(2.6) cm) than movements to IP(1&2) (2.2(2.5) cm and 1.3(2.4) cm, respectively). For movements starting at the rightmost IHP, this pattern was reversed (i.e., the hand was positioned significantly more to the right of IP(1) at interception 1.9(2.5) cm) than for movements to IP(2) (0.3(2.6) cm) and IP(3) (0.1(2.3) cm). For movements starting from the middle IHP, the balls were intercepted at the same relative position for all three IPs (IHP(2): 1.7(2.9) cm, 0.8(2.5) cm, and –0.7(2.0) cm for IP(1–3), respectively).

AE_{FHP}. AE_{FHP} provides an index of the absolute accuracy of hand positioning at interception. The main effect of Experiment showed that AE_{FHP} differed significantly across experiments, being lowest in the Catching experiment (3.2(0.6) cm), moderate in the Grasping experiment (4.6(1.4) cm), and highest in the CAVE experiment (6.6(1.6) cm). The main effect of IP resulted from a more accurate hand positioning at IP(1) (3.9(1.2) cm) compared to IP(2&3) (5.4(1.3) cm and 5.1(0.9) cm, respectively).

Δ_{LHP}. Because direction reversals are viewed as evidence for online control (e.g., Dessing et al., 2002; Montagne et al., 1999), it was deemed interesting to analyze the total path length of the direction reversals present in a given trial as represented by Δ_{LHP} (see Figure 3). The main effect of Experiment occurred because Δ_{LHP} was significantly larger in the Catching experiment (6.5(3.5) cm) than in the CAVE experiment (3.1(2.8) cm), whereas neither Δ_{LHP} differed significantly from that obtained in the Grasping experiment (4.7(4.1) cm). The main effect of IP resulted from significantly larger direction reversals when the ball passed at IP(2&3) (5.3(3.0) cm and 5.7(3.7) cm, respectively) than when it passed at IP(1) (3.1(2.8) cm). The main effect of IBP showed that Δ_{LHP} was significantly larger for balls moving outward (i.e., approaching from IBP(1); 5.9(4.0) cm) than for balls moving inward (i.e., approaching from IBP(2); 3.6(2.2) cm). Δ_{LHP} was larger the further to the

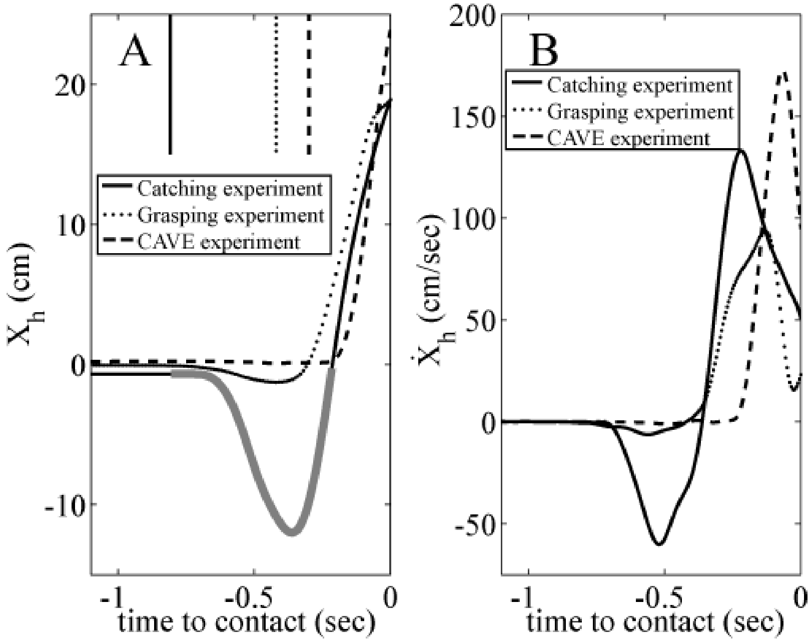

FIGURE 3 Representative kinematic profiles of lateral hand position (LHP; Panel A) and lateral hand velocity (Panel B) with respect to the time to contact of single trials of a single subject. These trials correspond to the condition with the hand initially at initial hand position(2), with a ball trajectory from initial ball position(1) to interception point(3). Solid lines correspond to the Catching experiment, dotted lines to the Grasping experiment, and dashed lines to the CAVE experiment. The vertical lines in the top of Panel A indicate the moments of initiation for the different profiles. The thick gray part of the solid curve indicates the part of the trajectory for the Catching experiment that is taken into account by the variable Δ_{LHP}: It is the integrated path length of the direction reversals (i.e., twice its amplitude). For the trajectories presented for the Grasping and CAVE experiments, no direction reversals were present after initiation, resulting in $\Delta_{LHP} = 0$.

right the hand started, resulting in a main effect of IHP (2.2(2.2) cm, 5.0(3.6) cm, and 6.9(3.9) cm for IHP(1–3), respectively; Δ_{LHP} for IHP(1) differed significantly from Δ_{LHP} for IHP(2&3)).

Post hoc analyses of the IP × IBP interaction showed that, only for balls starting at IBP(1), the path length of direction reversals was significantly smaller for balls moving toward IP(1) than for balls moving toward IP(2&3); post hoc analyses of the Experiment × IP × IBP interaction revealed that this pattern was present for all three experiments. In the CAVE experiment, Δ_{LHP} was also significantly larger for balls moving from IBP(2) to IP(1) than to IP(3). In addition, this three-way interaction revealed that the main effect of IBP (i.e., Δ_{LHP} [IBP(1)] > Δ_{LHP} [IBP(2)]) was only significant for balls approaching IP(2) in the CAVE and Catching experiments and for balls approaching IP(3) in the Grasping experiment. The path length of direction reversals differed significantly between the experiments for the ball trajectories defined by the following combinations of IBPs and IPs: IBP(1)/IP(2) (Δ_{LHP} [Catching] > Δ_{LHP} [CAVE]); IBP(2)/IP(1) (Δ_{LHP} [CAVE] < Δ_{LHP} [Catching and Grasping]); and IBP(2)/IP(3) (Δ_{LHP} [Catching] > Δ_{LHP} [CAVE and Grasping]). Figure 4A to 4C shows this pattern of results.

The IP × IHP interaction was significant because for each IHP the direction reversals followed a longer path the longer the distance to be traveled by the hand (i.e., the IHP–IP distance). For each IP, a similar pattern was present (although for IP(1), Δ_{LHP} was only larger for IHP(1) than for IHP(3)). Post hoc analyses of the Experiment × IP × IHP interaction revealed that, although this pattern (i.e., the general IHP–IP distance dependence) was present for all three experiments, the differences between the conditions were in general smaller for the CAVE experiment than for the Catching experiment (see Figure 4D–F), reflecting the main effect of Experiment.

The IBP × IHP interaction revealed that the main effect of IBP (i.e., Δ_{LHP} [IBP(1)] > Δ_{LHP} [IBP(2)]) was only present when the hand started at IHP(2&3). Moreover, for balls starting from both IBPs, the direction reversals were significantly larger the further the hand started to the right (IBP(1): 1.9(1.9) cm, 6.8(4.8) cm, and 8.9(5.9) cm for IHP(1–3), respectively; all post hoc comparisons significant; IBP(2): 2.5(2.6) cm, 3.3(2.4) cm, and 4.9(2.5) cm for IHP(1–3), respectively; difference only significant between IHP(2) and IHP(3)).

Number of MRs. Another measure related to the direction reversals is the number of MRs (which are basically large direction reversals). The number of MRs allows one to determine to what extent differences in the path length of direction reversals were caused by differences in number and/or amplitude of direction reversals. This variable was thus only tested for the factors that yielded significant main effects for Δ_{LHP} (i.e., all four factors). The number of MRs was significantly influenced by the factors Experiment, $\chi^2(2, N = 8) = 10.75, p < .01$; IP, $\chi^2(2, N = 8) = 9.80, p < .01$; and IHP, $\chi^2(2, N = 8) = 12.25, p < .005$. There were (a) significantly fewer MRs in the CAVE experiment (0.33(0.27)) than in the Catching (0.77(0.16)) and Grasping (0.55(0.35)) experiments, (b) significantly fewer MRs for balls approaching IP(3) (0.41(0.21)) than for balls approaching IP(2) (0.67(0.26); IP(1): 0.57(0.28)), and (c) significantly fewer MRs when starting from IHP(1) (0.41(0.22)) than when starting from IHP(3) (0.65(0.26); IHP(2): 0.60(0.26)). The significant effects of Experiment and IHP were similar to the corresponding main effects obtained for Δ_{LHP}, which suggests that the variations in Δ_{LHP} over the Experiment and IHP conditions resulted at least in part from differences in the number of MRs, whereas the variations in the path length of direction reversals over IBPs and over IPs were caused mainly by variations in the MR amplitudes.

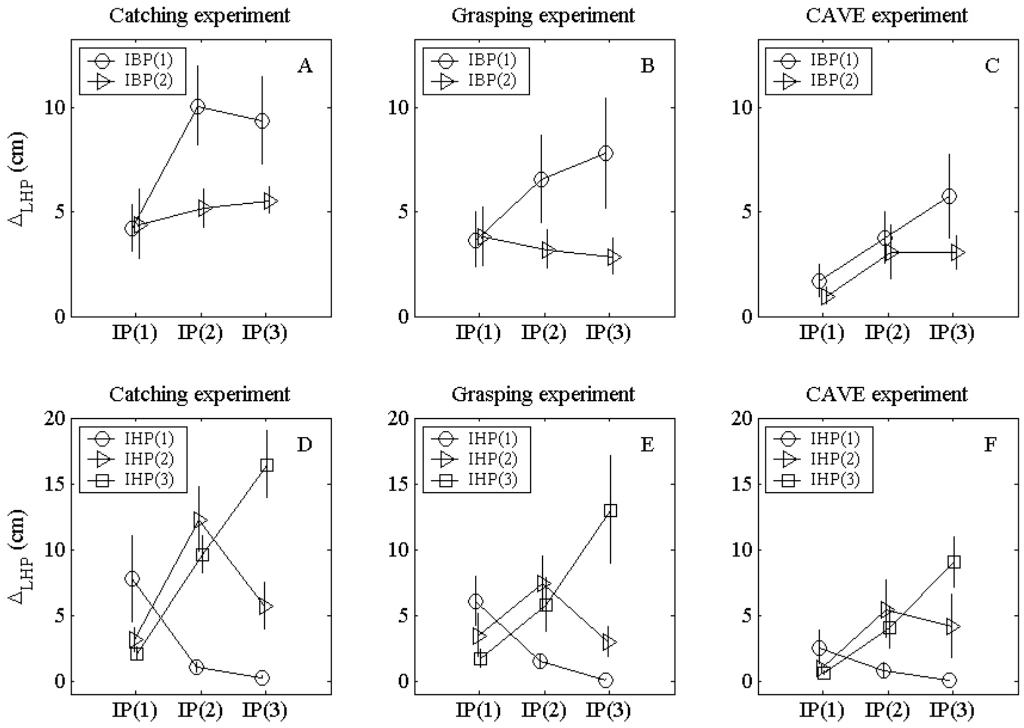

FIGURE 4 Mean values of path length of direction reversals (Δ_{LHP}; averaged over participants) as a function of interception point (IP) presented separately for the Catching experiment (A and D), the Grasping experiment (B and E), and the CAVE experiment (C and F) and for each initial ball position (IBP = A–C) and initial hand position (IHP = D–F). Error bars indicate standard errors. The numbers 1 through 3 (IP and IHP) and 1 to 2 (IBP) refer to the lateral position (1 = closest to the participant).

NintJerk$_{abs}$. Nintjerk$_{abs}$ is an index of the smoothness of the movement and as such quantifies irregularities in the kinematic profiles; such irregularities are often interpreted as reflections of feedback-based adjustments during the movement. A main effect of Experiment occurred because movements in the CAVE experiment (19.95(7.12) m/sec^3) were significantly smoother than in the Catching (40.17(9.53) m/sec^3) and Grasping (32.09(15.86) m/sec^3) experiments. In addition, a main effect of IHP was present because movements were significantly smoother when the hand started from IHP(1&2) (26.63(7.78) m/sec^3 and 28.60(10.81) m/sec^3, respectively) than from IHP(3) (36.98(11.77) m/sec^3).

Post hoc analyses of the significant IBP × IHP interaction revealed that, for balls starting from IBP(1), the interception movements were significantly smoother the further the hand started to the left (23.29(7.90) m/sec^3, 32.21(13.38) m/sec^3, and 39.24(12.91) m/sec^3 for IHP(1–3), respectively), whereas for balls starting from IBP(2), the movements were significantly smoother when the hand started from IHP(2) (24.99(8.59) m/sec^3) than from IHP(1&3) (29.97(7.95) m/sec^3 and 34.72(10.98) m/sec^3, respectively). When the hand started from IHP(1), the movements toward balls approaching from IBP(1) were significantly smoother than toward balls approaching from IBP(2), but when the hand started from IHP(2&3), the effect was in the opposite direction.

Number of velocity peaks. Another measure related to kinematic adjustments is the number of velocity peaks, which may help to interpret the source of movement irregularities (i.e., lack of smoothness). Some movements are irregular because they involve multiple submovements (and hence contain a higher number of velocity peaks), whereas other movements are irregular because of other variations in the kinematic profile. Thus, the number of velocity peaks was only tested for the factors that yielded significant main effects for NintJerk$_{abs}$ (i.e., Experiment and IHP) and was found to be significantly influenced only by the factor Experiment, $\chi^2(2, N = 8) = 14.25, p < .005$: There were significantly less velocity peaks in the CAVE experiment (1.38(0.32)) than in the Catching and Grasping experiments (2.15(0.25) and 1.68(0.47), respectively). This result corresponded to that obtained for NintJerk$_{abs}$, which suggested that the higher smoothness of movements in the CAVE experiment was caused partly by a smaller number of velocity peaks. The main effect of IHP for NintJerk$_{abs}$, however, must have been mainly caused by kinematic irregularities not captured by the number of velocity peaks because there was no significant effect of IHP on the number of velocity peaks.

DISCUSSION

The goal of this study was to evaluate the usefulness of stereoscopic visual displays of the kind that are commonly used in VR setups for experimental investigations of catching. A variety of ball trajectories and IHPs were used to decrease the predictability of the conditions for the participants and to create a broad testing range for the comparison of regular catching with catching using stereoscopic visual displays. This discussion mainly focuses on significant (main and interaction) effects of the factor Experiment (i.e., the behavioral differences of catching real and virtual balls) because these effects are pertinent to our research question.

Due to technical difficulties, the statistical analysis of the grasp parameters did not include the data obtained in the CAVE experiment. Nevertheless, the comparison between the Catching and Grasping experiments is still valuable for the research question because it provides insight into the influence of the absence of actually catching an object (as was also the case in the CAVE experiment) on grasping performance. In the Catching experiment, the PA was affected by the initial lateral position of the ball and the lateral position of the initiation point, whereas such effects were absent in the Grasping experiment. Apparently, in real catching, the closing of the hand is adjusted to the direction of ball impact, which played no role in the Grasping experiment. The timing of the grasp, however, did not differ between the two experiments. The absence of grasp parameters for the CAVE experiment precluded an investigation of timing aspects in this experiment and thus a comparison with the Catching and Grasping experiment in this regard. Rushton and Wann (1999) reported realistic timing patterns for participants catching virtual balls with a straight, head-on approach (i.e., requiring no substantial hand movements), but the degree to which the timing of grasping actions in the CAVE resembles that of real catching remains to be established in future experiments.

With respect to the lateral hand movements toward the IP, real catching and grasping only differed in the accuracy of the hand position at interception, whereas real catching differed from catching in the CAVE along many dimensions. Compared to real catching, hand movements in the CAVE were initiated later, less accurate (viz., larger AE_{FHP}), smoother (viz., smaller $NintJerk_{abs}$ and less velocity peaks), and more directly aimed at the final hand position (viz., smaller Δ_{LHP} and less MRs). Despite these quantitative differences, the qualitative effects obtained for the path length of direction reversals were rather similar for the three experiments (see Figure 4).

In all likelihood, the quantitative differences found between real catching and catching virtual ball trajectories in the CAVE are not unrelated. For instance, the well-known speed–accuracy trade-off (e.g., Fitts, 1954) dictates that fast goal-directed movements are less accurate than slower ones, which may explain why the absolute errors in hand position at interception were larger in the Grasping and CAVE experiments than in the Catching experiment in which the catching movements were initiated earlier. Furthermore, the number of velocity peaks (and thus the smoothness) has been shown to increase with increasing movement time for an interceptive pointing task (cf. Lee, Port, & Georgopoulos, 1997), and the same has been suggested for the amplitude of MRs (and thus path length of direction reversals) on the basis of modeling work (Dessing et al., 2002). Thus, the differences between the experiments with regard to these variables may have (partially) resulted from the delayed initiation in the CAVE. So, the key question appears to be "What caused this delayed initiation?"

Although we have not sufficient information to provide a definite answer to this question, it might be useful to speculate about various possibilities. A first option is that the observed difference in the timing of movement initiation was caused by differences in the retinal optics. However, this explanation is unlikely because the movement-optics delay was excluded from the CAVE experiment and because similar ball trajectories (and thus similar retinal optics) were presented in all experiments. These considerations imply that movements were not initiated solely on the basis of information about changes in the optical contour on the retina such as looming (e.g., Michaels, Zeinstra, & Oudejans, 2001) or τ (e.g., Lee, 1976; Savelsbergh et al., 1991).

A potentially relevant difference between the real environment and the CAVE's visual displays was the background: Whereas in the CAVE the background was completely dark, in the real environment a dark background was constructed using black sheets while the room was illuminated. Thus, although the color of the background was similar in both experiments, the sheets may still have provided depth information in the real environment. However, it is also unlikely that this caused the delayed initiation because Van der Kamp, Savelsbergh, and Smeets (1997) demonstrated that a degraded environment (such as the CAVE in this study) results in earlier rather than later initiation.

The observed differences between the Catching and CAVE experiments may have been caused in part by the difference between real catching and the grasping task. Even though no significant difference between the Catching and Grasping experiments was found for the moment of initiation, the other dependent variables in the Grasping experiment always assumed values situated between those observed in the Catching and CAVE experiments, suggesting that the Grasping experiment in a sense represented an intermediate situation between real catching and simulated catching in the CAVE. Of course, the Grasping experiment and the CAVE experiment had in common that no actual interception occurred. Indeed, participants reported difficulties with the grasping task because they did not know how well they were performing (i.e., whether their hand was at the right position at "interception"). Such reports are consistent with the fact that the absolute error of performance was larger in the grasping task than in real catching. This suggests that not only tactile information associated with grasping a ball (here available by means of the ball attached to the hand) is important in catching performance but also ball impact (cf. Zaal & Michaels, 2003). Because this information is only available at the moment of interception, its potential influence may reside in providing a natural form of knowledge of results, which may have been instrumental in refining catching performance in a given experimental setting (for instance in terms of the accuracy of hand positioning at interception).

Another factor that definitely differed between the real and virtual environment was lens accommodation (Bingham et al., 2001; Wann et al., 1995): Accommodation is only correct when the virtual ball is at the same distance from the eye as the projection screen (i.e., at 2.45 m in this experiment; on average the participants initiated their movements before the virtual ball reached this distance). The closer fixation distance at initiation might seem to necessitate an earlier rather than a later initiation, but the current lack of knowledge with regard to the extent in which accommodation (and its decoupling from vergence for stereoscopic vision) influences movement initiation of interceptive actions prevents definite conclusions about the role of this factor in this study. One way to examine this role would be to vary the position of the participant relative to the visual display (and thus the magnitude of lens accommodation; see also Bingham et al., 2001; Zaal & Michaels, 2003) when catching virtual balls.

Last, participants could have used a different strategy for catching real and virtual balls. Whereas the abundant presence of direction reversals in the Catching experiment suggests the use of a strategy based on online control (cf. Dessing et al., 2002; Montagne et al., 1999), participants may have anticipated making less and/or smaller direction reversals in the CAVE (e.g., by predicting the location of the IP) and thus traveling a shorter distance resulting in later initiation. Although this possibility cannot be ruled out completely, MRs in the CAVE experiment occurred sufficiently often (on average 0.33 per trial) to assume that an online control strategy was used in the CAVE as well.

In conclusion, some aspects of performance were qualitatively similar when comparing catching real balls with catching virtual balls presented on stereoscopic visual displays (e.g., the interaction effects for the path length of direction reversals). This suggests that such visual displays might be useful in addressing certain aspects of catching. However, simulated catching of a virtual ball presented on a visual display differed quantitatively from real catching. This suggests that, given the current technology, stereoscopic visual displays cannot be meaningfully used to study dynamical models of the perceptual guidance of interceptive actions (e.g., Dessing et al., 2002; Peper et al., 1994; see also Smeets & Brenner, 1995) because these generally make predictions about specific details of the entire catching trajectory, that is, from initiation to interception. On the other hand, determining the origin of the effects found in this study (e.g., the delayed initiation in the CAVE experiment) may provide valuable insights into the way in which perceptual information is used in the control of interceptive actions.

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