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Deceiving Oneself About Being in Control: Conscious Detection of Changes in Visuomotor Coupling

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Previous research has demonstrated that compensatory movements for changes in visuomotor coupling often are not consciously detected. But what factors affect the conscious detection of such changes? This issue was addressed in 4 experiments. Participants carried out a drawing task in which the relative velocity between the actual movement and its visual consequences was perturbed. Unconscious compensatory movements and conscious detection rates were simultaneously recorded. There was an invariant relationship between the extent of the change and its conscious detection that was proportional to the initial drawing velocity. This suggests that conscious change detection relies on a system that integrates visual and motor information—as, for instance, suggested by the internal model theory of motor control. Figural discrepancies increased the detection rates, indicating that additional cues for the what system facilitate conscious change detection.

Effective action control requires the establishment of flexible couplings between movements and their perceptual consequences. Prior research has demonstrated that individuals often unconsciously adjust their movements to changes in visuomotor couplings. The aim of this study was to investigate how such changes are consciously detected. Before we report the results of four experiments, we briefly review theories and empirical evidence relevant to this question.

The two-systems theory of visual perception (Bridgeman, 2000; Milner & Goodale, 1995; Rossetti & Revonsuo, 2000) distinguishes two separate streams of processing in the visual system that serve different functions. The *what path* processes information that is needed for the conscious identification of objects (e.g., form and color). The *how path* processes information that is needed for online movement control (e.g., location in space) and is assumed not to be consciously accessible. Accordingly, conscious detection of changes in visuomotor couplings should occur only if a particular aspect of these changes is picked up by the *what system*. Otherwise, the movement should be adjusted without conscious detection of the change.

Numerous empirical studies have provided evidence for these assumptions. For instance, one can accurately point to a target that is displaced without consciously perceiving the displacement (Bridgeman, Lewis, Heit, & Nagle, 1979). Likewise, the amplitude (Goodale, Pelisson, & Prablanc, 1986) and orientation (Prablanc & Martin, 1992) of reaching movements can be adjusted without conscious detection of the target displacements (Pelisson, Prablanc, Goodale, & Jeannerod, 1986). Castiello, Paulignan, and Jeannerod (1991) found that participants started to correct for displacements of visual targets long before these displacements were detected. Further experiments by Lackner and DiZio (2000) showed that one can also unconsciously adjust movements to perturbations created by Coriollis forces. Pisella et al. (2000; see also Day & Lyon, 2000) instructed participants to interrupt pointing movements when a target suddenly jumped from a go to a no-go location. The participants were often unable to stop correction of the pointing movement when the target jumped to the no-go location. If a change to no-go was indicated by a color change, such corrections did not occur. This seems to imply that one cannot voluntarily suppress movement corrections when the how path is provided with corresponding information.

The internal model theory of motor control (Frith, Blakemore, & Wolpert, 2000; Wolpert & Kawato, 1998) suggests an additional answer to the question of how changes in visuomotor coupling are consciously detected. According to this theory, motor control involves two functionally different components, inverse models and forward models. Inverse models provide the motor commands necessary to achieve desired consequences. Forward models predict the sensory consequences of each motor program to be executed (cf. von Holst & Mittelstaedt, 1954). Furthermore, it is assumed that one is aware of the desired and the predicted consequences of movements but normally not aware of the discrepancies between the predicted and the actual sensory consequences of movements. A study by Fourneret and Jeannerod (1998) has provided evidence for this assumption. Participants in this study traced a straight line by moving a stylus on a writing pad. In some trials, angular perturbations (−10° to 10°) were introduced be-

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tween the actual movement and its visual consequences on the screen. Participants judged their movements to be straight ahead even when they were actually bent.

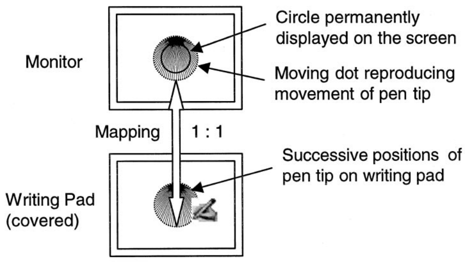
However, the discrepancy between the predicted and the actual sensory consequences of movements can influence the intensity of sensations, as demonstrated in a series of studies in the tactile domain (Blakemore, Frith, & Wolpert, 1999; Blakemore, Wolpert, & Frith, 1998; Weiskrantz, Elliott, & Darlington, 1971). In one of these studies (Blakemore et al., 1999), tactile stimuli were applied to the palm of the right hand. The temporal and spatial relationships between the left-hand movement and the tactile stimulation on the right hand were parametrically varied using two robot arms—one moved by the participant, the other applying the tactile stimulation. Participants judged the degree of ticklishness of this stimulation. The longer the temporal delay or the higher the spatial deviation between the self-produced movement and the tactile stimulus, the higher the ticklishness ratings were. This suggests that the experience of ticklishness was proportional to the discrepancy between the predicted and the actual tactile feedback that followed the movement. This interpretation is also supported by neurophysiological evidence (Blakemore et al., 1998).

In Blakemore et al.'s (1999) tickling study, there was no indication that participants were aware of the spatial and temporal delays between their movements and their tactile consequences, which suggests that discrepancies between the predicted and the actual consequences of the movements affected sensation without being consciously detected. Recent studies in the visual domain have varied the angular (Farrer et al., 2003; Fourneret & Jeannerod, 1998; Franck et al., 2001; Slachevsky et al., 2001; van den Bos & Jeannerod, 2002) or temporal (Franck et al., 2001; Leube, Knoblich, Erb, Grodd, et al., 2003) discrepancies between hand movements and the corresponding visual feedback. These studies showed that such discrepancies were consciously detected when they exceeded a certain threshold. Jeannerod (1999, 2003; see also Georgieff & Jeannerod, 1998) proposed that conscious detection of such deviations depends on a specific brain system (the *who system*). Another possibility is that conscious detection also depends on discrepancies between the predicted and the actual consequences of movements (Frith et al., 2000). The threshold for conscious detection of the discrepancies might be relatively high and, therefore, sensation might be affected before discrepancies are consciously detected.

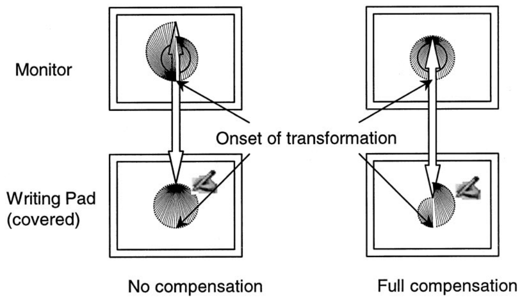
The aim of the present study was to extend the empirical evidence about conscious detection of changes in visuomotor coupling. This might also provide further hints as to the underlying mechanisms of change detection. In particular, we explored how different variables affect the relationship between the extent of a velocity transformation and its conscious detection. We also attempted to extend previous findings by using a novel setting that differed from the settings used in previous studies in one or several of the following ways: (a) continuous instead of discrete movements, (b) intentionally driven instead of stimulus-driven movements, (c) ample time for change detection instead of the necessity to act quickly, (d) discrepancies in velocity instead of angular or temporal discrepancies alone, and (e) synchronous measurement of conscious detection as well as nonconscious corrections. The use of discrete, stimulus-driven movements and, in particular, the necessity to act very quickly characterize many of the earlier tasks and might have led to an underestimation of conscious change detection and to an overestimation of unconscious movement adjustment.

Figure 1 illustrates the task. Participants drew circles on a writing pad and observed the visual consequences of the movement (in the form of a moving dot) on a monitor. At the beginning of each trial, the visual feedback corresponded exactly to the movement (see Figure 1A). Later in the trial, a change in relative velocity occurred. The dot movement on the screen was accelerated relative to the actual movement of the pen tip on the writing pad. This resulted in an increase of the radius of the dot movement on the screen if drawing on the writing pad was continued in the same way as before (see Figure 1B, left panel). Alternatively, if circles with a smaller radius were drawn, the observed movement remained the same (see Figure 1B, right panel). Participants were instructed to lift the pen from the writing pad as soon as they noticed that there might have been a change.

We conducted four experiments. The first experiment explored whether movement velocity moderates the conscious detection of changes in visuomotor coupling. The second experiment investigated whether conscious change detection is affected by the availability of an external signal that guides the movement. The third experiment assessed whether spatially asymmetrical changes are more likely to be detected than spatially symmetrical changes. Finally, Experiment 4 tested whether (a) the conscious detection of changes in visuomotor coupling is based only on local discrepan-



A: Drawing, Circles 1–3 (0–6 s)



B: Onset of transformation, Circle 4 (6–8 s)

Figure 1. Illustration of the circle drawing task as performed in the medium-velocity group. A: The first three circles in each trial were drawn under a 1:1 mapping. B: While participants drew the fourth circle, there was a sudden change in relative velocity. The dot movement was accelerated relative to the movement of the pen tip. If the change was not compensated for, the trajectory of the moving dot on the monitor changed (left). If the change was fully and immediately compensated for, the trajectory of the moving dot on the screen remained unchanged (right).

cies or (b) information about discrepancies can be accumulated across longer time spans.

Experiment 1

Two factors were systematically varied in the first experiment: the extent of the relative velocity change (0%–80% acceleration of the dot movement on the screen relative to the movement of the pen tip on the writing pad) and drawing velocity. Conscious detection should vary systematically as a function of the extent of the change. The condition without change (0% acceleration) served to identify biases. If participants developed a general tendency to suspect changes, changes should be reported even when not present. Prior evidence suggests that participants should unconsciously adjust their movements to compensate for the change. However, suppressing compensation might actually be an effective strategy to detect changes in relative velocity: If compensation could be suppressed, visual deviations would become more salient.

We also varied drawing velocity in order to determine whether conscious detection of the change depends on the absolute discrepancy between the actual movement and its visual consequences. In this case, the detection rates should be affected by drawing velocity. The faster the movement, the larger the discrepancy that arises from the same relative velocity change in a given time interval. Thus, the same change should be detected more often at faster drawing velocities. However, there might also be a multiplicative relationship between initial velocity and conscious detection. In this case, drawing velocity should not affect the detection rates. This would suggest that conscious detection of the change does not rely on a system that processes either visual or movement-related information per se but on a system that integrates both types of information.

Method

Participants. Forty-two participants (33 women, 9 men), all students at the University of Munich, Munich, Germany, took part in the experiment. They ranged from 20 to 39 years old. All participants were right-handed and had normal or corrected-to-normal vision. They received payment for their participation. Fourteen participants were assigned to each experimental group (slow, medium, and fast drawing velocity).

Apparatus. The visual stimuli were presented on an Apple Vision 17-in. (43.18-cm) monitor with a horizontal resolution of 800 pixels and a vertical resolution of 600 pixels. The vertical sync frequency was 75 Hz. The movements of the pen tip were recorded using a Wacom (Krefeld, Germany) writing pad with a sampling rate of 75 Hz, a horizontal resolution of 15,000 dots, and a vertical resolution of 11,250 dots. An Apple Power PC controlled these devices and the control monitor. The sampling rate of the writing pad was synchronized with the screen refresh rate. The constant delay between visual effect and the movement of the pen tip was about 13 ms.

Procedure. Participants were seated in front of the stimulus monitor at a distance of approximately 60 cm. The writing pad was located between the monitor and the participant, and an attached cover prevented participants from seeing their drawing hand. Participants went through 20 training trials to familiarize themselves with the use of the writing pad. In each trial, they tracked a circular target that moved with constant velocity. The location of the pen tip was indicated by a solid, circular dot and exactly corresponded to the movement of the pen tip on the writing pad. Neither the target nor the dot representing pen-tip position left a trace on the screen. In each training trial, the target completed five full circles with an eccentricity of 9.0° of visual angle for the full circle. The target velocities were 11.3, 14.1, and 18.9 cm/s in the slow-, medium-, and fast-velocity groups, respectively. Accordingly, completion of a full circle took 2.5, 2.0, and 1.5 s in the respective groups. The movement of the tracking signal mimicked a possible trajectory in the baseline condition of the main experiment. Whenever the target reached the 12 o'clock position, a short beep (200 ms, 1000 Hz) was sounded. Participants practiced the experimental task in a second training phase of 10 trials. In some trials, large changes in relative velocity occurred (e.g., 100%: from 1:1 to 1:2) to illustrate the nature of the change participants should look for.

The main experiment consisted of 120 trials. At the start of each trial, a full circle subtending 7.0° of visual angle appeared in the screen center. It remained visible throughout the trial. In addition, a quadratic box subtending 1.0° horizontally and vertically appeared 1.5° above the 12 o'clock position of the circle. Participants clicked the box and started drawing. They were instructed to pass the 12 o'clock position at the time of the beep. Consecutive beeps served to indicate the end of each interval at which a full circle should be completed and were used to vary the drawing velocity between the three experimental groups. The interval between two consecutive beeps was 2.5, 2.0, and 1.5 s in the slow-, medium-, and fast-velocity groups, respectively.

During the first three intervals, the mapping between screen and writing pad was 1:1 (see Figure 1A). This phase served to reestablish the 1:1 mapping in each trial and to avoid long-term adaptation (Kohler, 1962). The critical manipulation took place during the fourth interval: In the no-change condition (20% of the trials), the mapping between writing pad and screen remained 1:1. In the four remaining conditions (20% of the trials each), the movement of the dot on the screen was accelerated relative to the movement of the pen tip on the writing pad by 20%, 40%, 60%, or 80%. This resulted in a 1.2:1, 1.4:1, 1.6:1, or 1.8:1 ratio of the velocity of the dot on the screen to the actual velocity of the pen tip on the writing pad (see Figure 1B). The change could occur at any time during this interval. Note that the onset of the change did not create a visible discontinuity (e.g., a flicker) in the dot movement. Participants lifted the pen as fast as possible when they thought they had detected a change. If the pen was lifted, the trial ended. Otherwise, participants continued to draw circles. A trial ended after 12.5, 11.0, and 8.5 s in the slow-, medium-, and fast-velocity groups, respectively. Thus, participants had ample time (between 2.5 and 5.0 s) to lift the pen in response to a change.

Results

Detection and response times (RTs). Figure 2 displays the pen-lift rates, which were the main dependent variable for change detection, as a function of the relative velocity change for the different experimental groups. In all groups, larger changes were more often detected. The detection rates followed a logistic function. There were no systematic differences between the experimental groups. Accordingly, a mixed analysis of variance (ANOVA) with the between-participants factor drawing velocity (slow, medium, and fast) and the within-participant factor acceleration (0%, 20%, 40%, 60%, and 80%) revealed a significant main effect of acceleration, $F(4, 156) = 464.4$, $p < .001$, but no significant effect of drawing velocity, $F(2, 39) = 1.1$, $p = .33$, and no significant Acceleration × Drawing Velocity interaction, $F(8, 156) = 0.7$, $p = .68$.

In a second step, a logistic function was fitted to the observed pen-lift rates. The R^2 of these fits ranged from .77 to 1.0 ($M = .97$) for individual participants. Thus, the logistic function captured the relation between the extent of relative velocity change and conscious detection quite well. The average point of highest uncertainty (50% change detection) was reached at an acceleration of 47% and did not significantly differ between the slow- (46%),

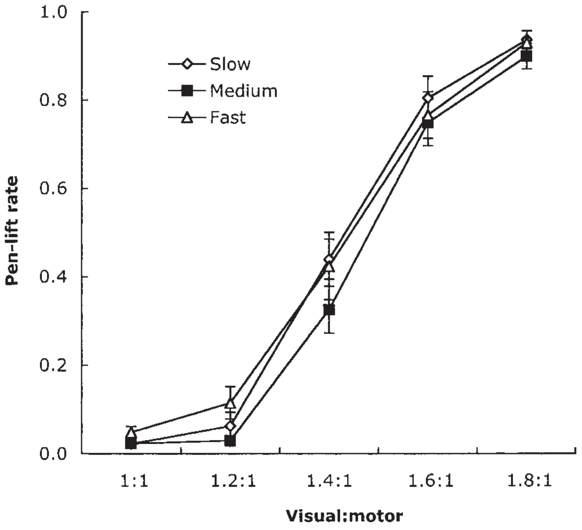


Figure 2. Pen-lift rates in Experiment 1 in the three experimental groups (slow, medium, and fast drawing velocity) as a function of the change in relative velocity of the dot on the screen (visual) and the movement of the pen tip (motor). Error bars represent standard errors.

medium- (50%), and fast-velocity (45%) groups, *F*(2, 39) = 1.0, *p* = .39.

For conditions with sufficient numbers of pen lifts, the time to detect the change was also analyzed. The average time of pen lifts relative to the onset of the change was 1,318 ms (*SD* = 302), 1,096 ms (*SD* = 266), and 921 ms (*SD* = 212) in the 40%, 60%, and 80% conditions, respectively. A 2 × 3 mixed ANOVA with the between-participants factor drawing velocity (slow, medium, and fast) and the within-participant factor acceleration (40%, 60%, and 80%) again revealed a significant main effect of acceleration, *F*(2, 78) = 61.9, *p* < .001, but no significant main effect of drawing velocity, *F*(2, 39) = 0.2, *p* = .79, and no significant Acceleration × Drawing Velocity interaction, *F*(4, 78) = 1.7, *p* = .16.

Spatial parameters. This analysis aimed to determine to what extent participants compensated for changes in relative velocity that they did not consciously detect. We analyzed the position of the pen tip on the writing pad at the end of the third and fourth intervals for trials in which the pen had not been lifted. We used polar coordinates (radius and angle). The radius stands for the distance between the center of the drawn circle and the pen position on the writing pad. The angle indicates how well the participants met the 12 o'clock position (0°) at the time of the beep. The 1.8:1 condition was not included in the analysis because participants almost always detected the change in this condition. Figure 3 shows the radial component of the pen position before and after the relative velocity change. Prior to the onset of the change, the radial component was the same in all conditions. After the onset of the change, the radial component of the drawn circle was inversely proportional to the extent of the change. Thus, participants clearly compensated for the change without consciously detecting it.

To statistically confirm these results, we conducted a 4 × 2 repeated measurements ANOVA with the factors acceleration (0%, 20%, 40%, and 60%) and interval (before and after change). This analysis revealed a significant main effect of acceleration, *F*(3, 108) = 21.9, *p* < .001, as well as of interval, *F*(1, 36) = 137.0, *p* < .001, and a significant Acceleration × Interval interaction, *F*(3, 108) = 23.1, *p* < .001. The overall mean for the angular component relative to the 12 o'clock position was −5.2° (*SD* = 12.4°). There were no significant differences between different conditions for this variable. For the 40% and 60% conditions, one can assess whether there was a difference in the amount of compensation between trials in which the change was detected and trials in which the change was not detected because the pen-lift rates were closest to .50. There were no significant differences between these two types of trials.

Discussion

The results of the first experiment demonstrate that the detection rates for a sudden change in relative velocity between a drawing movement and its visual consequences nicely followed a logistic function. It is surprising that the initial drawing velocity had no effect. The functions for the fast, medium, and slow drawing velocity were virtually identical (see Figure 2). This implies that conscious detection of the change did not depend on the absolute discrepancy between drawing movements and their visual consequences. Rather, it varied as a function of a constant proportion of the initial velocity of the drawing movement. This suggests that conscious detection of the change relied on a system that integrates visual and motor-related information, not on a system that processes either visual or motor-related information alone. The second result indicates that compensation for the change could not be suppressed, even though the participants continuously performed intentional actions. Participants adjusted their movements in response to the change even if they did not consciously detect it. There was no indication that conscious detection of the change led

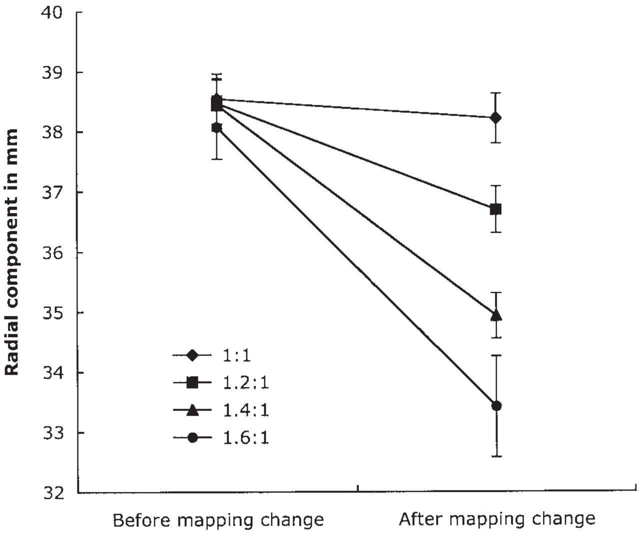


Figure 3. Radial component of pen position in Experiment 1 before and after the change in relative (dot on screen:movement of pen tip) velocity. Only data from trials in which the change was not detected are shown. Error bars represent standard errors.

to differences in this adjustment. Moreover, the adjustment was also proportional to the extent of the change.

Experiment 2

The aim of the second experiment was to investigate whether the sensitivity for changes in visuomotor coupling crucially depends on intentional control of action. To this end, we devised a tracking version of the circle-drawing task in which a visual signal continuously specified the required movement position. If the system providing the signals for the conscious detection of the change were specific to intentionally controlled actions, the detection rates for the tracking task should differ from the ones observed in the first experiment. They could be lower, because the system for change detection might be disengaged in reactive tasks. Alternatively, the distance between the tracking signal and the dot representing the pen movement might provide additional information about visual discrepancies, which might be more reliable than the difference between an expected event and an observed event. In this case, the detection rates should be higher. Finally, the same system might be used for conscious change detection, regardless of the exact nature of the task. In this case, the results should be the same as in Experiment 1.

Method

Participants. Fourteen new participants (10 women, 4 men), all students at the University of Munich, took part in the experiment. They ranged from 20 to 30 years old. All participants were right-handed and had normal or corrected-to-normal vision. They received payment for their participation.

Apparatus and procedure. These were the same as in the medium-velocity condition of Experiment 1, with the following exceptions: In each trial of the main experiment, the participants tracked a circular target that moved with a constant velocity of 2.0 s per circle (14.1 cm/s) and an eccentricity of 9.0° for the full circle. To get more fine-grained information for smaller accelerations, we accelerated the velocity of the dot on the screen relative to the movement by 0%, 15%, 30%, 45%, and 60%, resulting in 1:1, 1.15:1, 1.3:1, 1.45:1, and 1.6:1 mappings, respectively, after the change.

Results

The pen-lift rates were .05 ($SD = .07$), .08 ($SD = .12$), .25 ($SD = .19$), .47 ($SD = .22$), and .77 ($SD = .15$) for the 0%, 15%, 30%, 45%, and 60% acceleration conditions, respectively. A one-way repeated measures ANOVA with the factor acceleration (0%, 15%, 30%, 45%, and 60%) revealed a highly significant main effect, $F(4, 52) = 83.4$, $p < .001$. For each participant, a logistic function was fitted to the pen-lift rates. The R^2 for these fits ranged from .71 to .98 ($M = .90$). On average, the point of highest uncertainty (50% detection) was reached at an acceleration of 45%. A comparison with the medium-velocity group of Experiment 1 revealed no significant differences in pen-lift rates or in the point of highest uncertainty. The average RTs of 1,250 ms ($SD = 297$) and 1,101 ms ($SD = 315$) in the 45% and 60% acceleration conditions, respectively, show that it took longer to detect smaller changes. A t test confirmed that this difference was significant, $t(13) = 2.71$, $p < .05$.

To assess whether participants compensated for the change without consciously detecting it, we analyzed the radial component of the pen tip position before and after the change in relative velocity (see Experiment 1). We included only trials in which the change had not been detected. One participant was excluded from this analysis because he had always detected the change in the 60% acceleration condition. Figure 4 shows the results of the analysis. As in Experiment 1, the radial component of the circle drawn after the change was inversely proportional to the extent of the change. The data were entered into a 5 × 2 repeated measures ANOVA with the factors acceleration (0%, 15%, 30%, 45%, and 60%) and interval (before and after change). This analysis revealed significant main effects of acceleration, $F(4, 48) = 10.5$, $p < .001$, and interval, $F(1, 12) = 122.3$, $p < .001$, and a significant Acceleration × Interval interaction, $F(4, 48) = 21.0$, $p < .001$. Further analyses revealed that there were no systematic differences in compensation between trials in which the change had been detected and trials in which the change had not been detected.

Discussion

The results were the same as in Experiment 1. Conscious detection of the change in relative velocity followed a logistic function that was almost identical to the ones previously observed. Again, the extent of the adjustment of the drawing movement was proportional to the change and did not differ whether the change was detected or not. These results suggest that the same integrated visuomotor system that provided the signals for conscious detection in the intentional version of the task (see Experiment 1) also provided the signals for change detection in the reactive task.

Experiment 3

In the preceding experiments, the change in relative velocity affected the horizontal dimension and the vertical dimension to the same degree. With Experiment 3, we assessed the sensitivity for changes on a single dimension. In one experimental group,

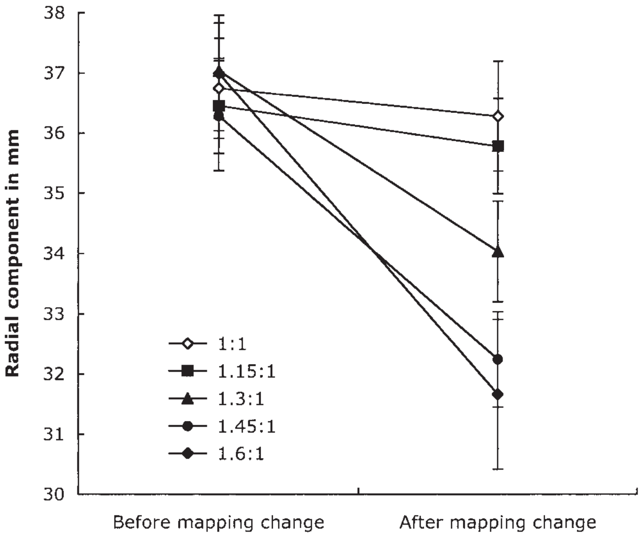


Figure 4. Radial component of pen position in Experiment 2 before and after the change in relative (dot on screen:movement of pen tip) velocity. Only data from trials in which the change was not detected are shown. Error bars represent standard errors.

changes in relative velocity occurred only on the horizontal dimension; in the other experimental group, they occurred only on the vertical dimension. Figure 5 illustrates the effects of the horizontal change. After the change, circular drawing movements produced horizontally elongated ellipses. Accordingly, production of a circular dot movement on the screen required drawing movements that followed a vertically elongated ellipse.

If the same relative velocity change is applied to one instead of two dimensions, the absolute discrepancy between movement-related and visual information becomes smaller. Thus, if conscious detection were based on the absolute discrepancies, the detection rates should be lower for the one-dimensional change than for the two-dimensional change. The two-systems theory of visual perception would suggest a different outcome. One-dimensional changes lead to an additional figural discrepancy between the actual movement and its visual consequences. Such figural discrepancies should provide effective cues for detection of the change because they should be picked up by the what system (Milner & Goodale, 1995). Therefore, detection rates should be as high or even higher for the one-dimensional than for the two-dimensional change, despite the smaller absolute discrepancies.

Comparing the two experimental groups allows one to determine whether there are asymmetries in the conscious detection of changes on the horizontal and vertical dimensions. Such asymmetries might occur because the vertical components of drawing movements might be more extensively controlled than their horizontal components (cf. Hollerbach, 1981).

Method

Participants. Twenty-eight new participants (21 women, 7 men), all students at the University of Munich, took part in the experiment. They ranged from 18 to 39 years old. All participants were right-handed and had normal or corrected-to-normal vision. They received payment for their participation. They were randomly assigned to the two experimental groups.

Apparatus and procedure. These were the same as in the medium-velocity condition of Experiment 1, with the following exceptions: In the horizontal-change group, the movement of the dot on the screen was accelerated relative to the movement of the pen tip only on the horizontal dimension (see Figure 5). In the vertical-change group, the movement of the dot on the screen was accelerated relative to the movement of the pen tip only on the vertical dimension. In both groups, the velocity of the dot on the screen was accelerated relative to the movement by 0%, 15%, 30%, 45%, and 60%, resulting in 1:1, 1.15:1, 1.3:1, 1.45:1, and 1.6:1 mappings, respectively, after the change.

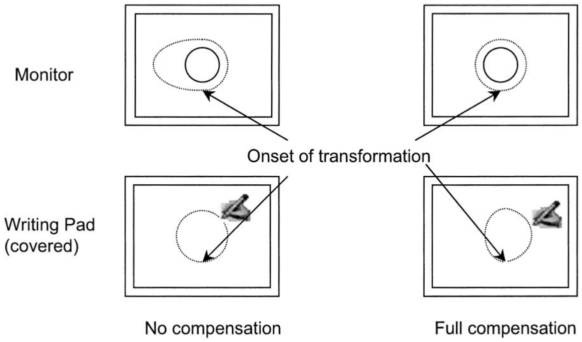


Figure 5. Illustration of the change applied in the horizontal-change group of Experiment 3. After the change, a circular movement on the writing pad led to a movement of the dot on the screen that followed a horizontally elongated ellipse (left). To produce a circular movement on the screen, the movement on the writing pad had to follow a vertically elongated ellipse (right).

Results

Figure 6 shows the pen-lift rates obtained in Experiment 3. They increased in an identical manner—as the change in relative velocity became larger—in both experimental groups. A two-way mixed ANOVA with the between-participants factor dimension (horizontal and vertical) and the within-participant factor acceleration (0%, 15%, 30%, 45%, and 60%) revealed only a highly significant main effect of acceleration, $F(4, 104) = 295.5$, $p < .001$. For each participant, a logistic function was fitted to the pen lift rates. The R^2 for these fits ranged from .79 to .98 ($M = .89$). In both groups, the average point of highest uncertainty (50% detection) was reached at an acceleration of 42%. In order to determine whether this value was significantly smaller than the 50% observed in the medium-velocity group of Experiment 1, we conducted a two-tailed *t* test. This test confirmed that the sensitivity for changes on one dimension was significantly higher than for changes on both dimensions, $t(40) = 2.36$, $p < .05$.

The average RTs were 1,417 ms ($SD = 283$) and 1,205 ms ($SD = 246$) in the 45% and 60% acceleration conditions, respectively. A mixed 2 × 2 ANOVA with the between-participants factor dimension (horizontal and vertical) and the within-participant factor acceleration (45% and 60%) revealed only a significant effect of acceleration, $F(1, 26) = 25.9$, $p < .001$. The main effect of dimension and the two-way Dimension × Acceleration interaction were not significant (both *p*s > .30). The analysis of spatial parameters showed the same pattern as in the previous experiments and, therefore, is not reported in detail.

Discussion

The results of Experiment 3 demonstrate that changes in relative velocity are easier to detect when they produce figural discrepancies between drawing movements and their visual consequences. A comparison with the detection rates observed in Experiment 1 revealed that the same change was more often detected when it was applied to only the horizontal or vertical dimension than when it was applied to both dimensions. The higher detection rate occurred despite the fact that one-dimensional changes led to a smaller absolute discrepancy between the drawing movement and its visual consequences. This result supports the assumption of the two-systems theory of visual perception (Milner & Goodale, 1995; Pisella & Rossetti, 2002). The one-dimensional changes produced additional figural discrepancies that were picked up by the what path and were, therefore, easier to detect. The lack of a difference between the horizontal- and the vertical-change group is also consistent with the assumption that the higher sensitivity for changes was due to figural discrepancies, because the same relative velocity change led to the same figural discrepancy regardless of which dimension it was applied to.

Experiment 4

In the last experiment, we addressed the issue of whether unconscious compensation for changes actually reduces discrepan-

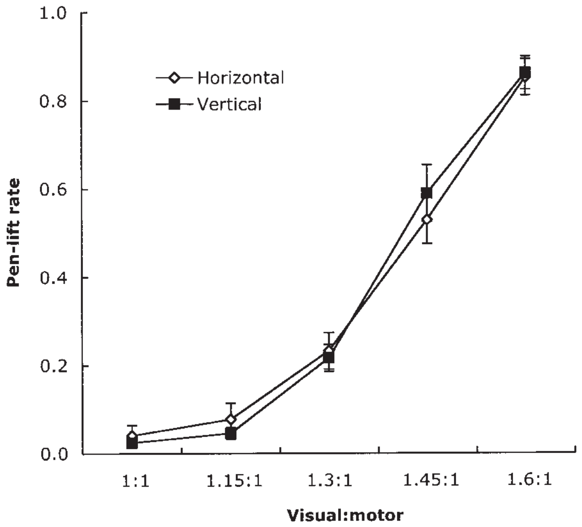


Figure 6. Pen-lift rates in Experiment 3 for the horizontal-change group and the vertical-change group as a function of the one-dimensional change in relative velocity of the dot on the screen (visual) and the movement of the pen tip (motor). Error bars represent standard errors.

cies that would be needed to consciously detect changes. If this is so, conscious detection rates should decrease when compensation is easier to achieve. One way to address this issue is to successively change the relative velocity between the actual movement and its visual consequences in small steps. We used two different increments of acceleration (12.5% and 25.0%), which were applied until the maximum change of 50% or 75%, respectively, was reached.

These manipulations also allowed us to determine whether evidence for discrepancies is accumulated over longer time periods. If conscious detection were exclusively based on local discrepancies, it should be impossible for participants to detect changes in the 12.5% increment condition because changes of this size were not detected in the preceding experiments. If evidence for discrepancies were accumulated, participants should be able to consciously detect changes that are successively introduced, even if each increment is below the detection threshold. In this case, the extent of the maximum transformation should also affect the detection rate because the more frequent the small increments, the more information can be accumulated.

Method

Participants. Fourteen new participants (10 women, 4 men), all students at the University of Munich, took part in the experiment. They ranged from 18 to 34 years old. All participants were right-handed and had normal or corrected-to-normal vision. They received payment for their participation.

Apparatus and procedure. These were the same as in the medium-velocity condition of Experiment 1, with the following exceptions: There were two levels of acceleration (50% and 75%) and two levels of increment (12.5% and 25.0%). Each combination made up 20% of the trials. There was no change in relative velocity during the remaining 20% of the trials. In the change trials, the movement of the dot on the screen was accelerated relative to the movement of the pen tip on the writing pad by increments of 12.5% or 25.0%. The first change could occur at any point during the interval between 4.0 and 6.0 s after the start of the trial. Further changes accelerated the dot on the screen by 12.5% or 25.0% until the maximal acceleration of 50% or 75% was reached. The temporal interval between the consecutive changes was constant (666 ms, corresponding to three increments per circle).

Results

The pen-lift rate in the condition without change was quite low (*M* = .09). The upper panel of Figure 7 shows the pen-lift rates in the remaining four conditions of Experiment 4. The average rates were .55 (*SD* = .26) and .65 (*SD* = .25) in the 50% and 75% acceleration conditions, respectively, and .56 (*SD* = .26) and .64 (*SD* = .25) for small and large increments, respectively. A two-way repeated measures ANOVA with the factors acceleration (50% and 75%) and increment (small and large) revealed signifi-

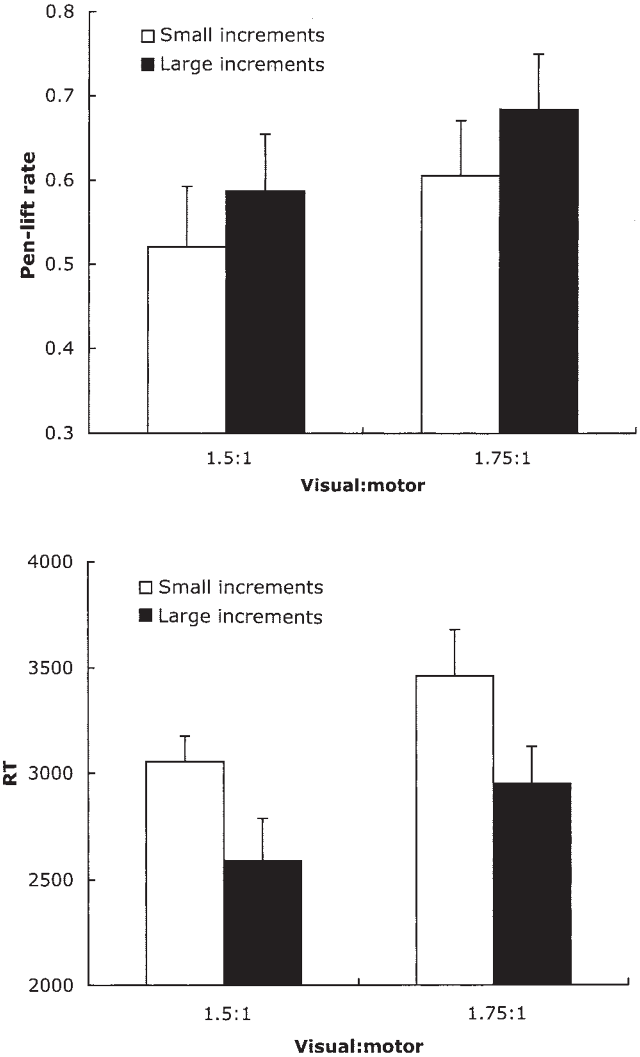


Figure 7. Pen-lift rates (upper panel) and reaction times (RTs, in milliseconds; lower panel) in Experiment 4 as a function of overall change in relative velocity (of the dot on the screen [visual] and the movement of the pen tip [motor]) and change increment. Error bars represent standard errors.

cant main effects of acceleration, $F(1, 13) = 12.9$, $p < .01$, and increment, $F(1, 13) = 7.0$, $p < .05$, but no significant Acceleration × Increment interaction ($p = .67$).

The lower panel of Figure 7 shows the RTs for those trials in which the change was detected. The average RTs relative to the time of the first increment were 2,822 ms ($SD = 604$) and 3,205 ms ($SD = 742$) in the 50% and 75% acceleration conditions, respectively, and 3,258 ms ($SD = 640$) and 2,769 ms ($SD = 706$) for small and large increments, respectively. A two-way repeated measures ANOVA with the factors acceleration (50% and 75%) and increment (small and large) revealed significant main effects of acceleration, $F(1, 13) = 18.5$, $p < .001$, and increment, $F(1, 13) = 33.4$, $p < .001$, but no significant Acceleration × Increment interaction ($p = .82$).

Discussion

The results of Experiment 4 show that the conscious detection of large changes in relative velocity was more difficult when changes were successively introduced in small steps. In the 12.5% increment condition, a 75% acceleration of the dot on the screen relative to the movement on the writing pad was detected in only 60% of the trials. The detection rate for a change of the same order was higher than 90% in Experiment 1 (compare Figure 2). This result seems to imply that compensation can obscure discrepancies, which could lead to the conscious detection of the changes in relative velocity. However, it does not imply that conscious detection is based only on local discrepancies. The changes could still be consciously detected when each of the successive increments was below the detection threshold. This seems to indicate that evidence about discrepancies can be accumulated.

General Discussion

This study aimed to explore the factors that affect the conscious detection of changes in visuomotor coupling and, in particular, of changes in relative velocity between drawing movements and their visual consequences. In four experiments, we assessed the influence of (a) initial velocity, (b) the intentional versus reactive nature of the task, (c) figural discrepancies, and (d) global versus local changes. The main results were as follows: (a) Detection rates were proportional to the initial velocity of the drawing movement, (b) they did not differ between an intentional and a reactive version of the task, (c) figural discrepancies increased the detection rates, and (d) detection was not exclusively based on local discrepancies.

The most striking result was that the relationship between the extent of the change in relative velocity and the conscious detection rates was very systematic (see Experiments 1–3) and, more important, invariant across different initial velocities (see Experiment 1). The functions describing this relationship look exactly like psychophysical functions relating sensory magnitude to stimulus magnitude. However, in this case, the stimulus dimension was not physical but, rather, visuomotor, implying that participants' conscious detection of changes in visuomotor coupling was systematically altered by what they were doing. This suggests that the signal for conscious change detection was generated by a system that integrates visual and motor information and that the signal was proportional to the discrepancy between these two sources of information.

The internal model theory of motor control (Frith et al., 2000; Wolpert & Kawato, 1998) can explain the generation of such a signal. According to this theory, one predicts the sensory consequences of each motor command and compares the predicted and the actual consequences of the movement. An error signal generated from such a comparison might well underlie the conscious detection of changes in visuomotor coupling as well as the unconscious adjustment of movements observed in the present experiments. The threshold for unconscious adjustment might simply be much lower than the threshold for conscious detection (Frith et al., 2000). This would also explain why there were no differences in detection between the intentional (see Experiment 1) and the reactive (see Experiment 2) version of the task, because it is assumed that predictions are generated for all movements. A recent functional MRI study that investigated what brain signals underlie the conscious detection of spatial discrepancies between hand movements and their visual consequences also seems to be consistent with the assumption that conscious detection is proportional to an error signal generated in the motor system (Leube, Knoblich, Erb, Grodd, et al., 2003). In the tactile domain, the error signal affected sensation without leading to conscious detection (Blakemore et al., 1999), which might again have been due to the threshold for conscious detection of discrepancies being higher than the threshold for changes in sensation (Frith et al., 2000).

Another interesting result was that one-dimensional changes in relative velocity (see Experiment 3) were more detectable than two-dimensional changes (see Experiments 1 and 2), although they led to smaller discrepancies in absolute terms. This suggests that figural discrepancies were used for conscious change detection. Obviously, this result further supports the assumption of the two-systems theory of visual perception (Milner & Goodale, 1995; Pisella & Rossetti, 2002; Rossetti & Revonsuo, 2000) that information being picked up by the what system becomes consciously available, whereas the information being picked up by the *how system* is normally not consciously available.

The assumption that processing in the what system is slower than processing in the how system actually provides another principle to explain change detection in the present experiments (cf. Pisella & Rossetti, 2002). The how system might correct movements before the what system receives enough cues to detect a change (e.g., in circle size). The result that evidence about discrepancies can be accumulated (see Experiment 4) could be explained by the assumption that information is retained longer in the what system. Consecutive subthreshold cues could be added and, at some point, cross the threshold for conscious detection. The assumption of different processing speeds can also explain the finding that unconscious adjustment of movements cannot be avoided, which was observed in this study and in earlier experiments (Pisella et al., 2000). Before control processes can kick in, movement correction has already taken place.

Thus, there are several possibilities for how one or more sources of information give rise to the relationship governing conscious detection of changes in visuomotor coupling. Recent studies of patients with disorders in the awareness of action seem to actually favor a multiple-source explanation. Patients with parietal lesions (Sirigu, Daprati, Pradat-Diehl, Franck, & Jeannerod, 1999) and schizophrenic patients with delusions of control seem to have problems in determining whether certain visual events reflect their own actions (Blakemore, Smith, Steel, Johnstone, & Frith, 2000;

Daprati et al., 1997; Franck et al., 2001; Frith, 1992; see also Kircher & David, 2003). Blakemore (2003) recently suggested that these problems might be due to the fact that a parietal-cerebellar system that detects discrepancies between movements and their consequences is dysfunctional in these patients. However, other studies have shown that patients with frontal lesions (Lhermitte, 1983, 1986; Marchetti & Della Salla, 1998; Slachevsky et al., 2001) and schizophrenic patients with formal thought disorder (Knoblich, Stottmeister, & Kircher, in press) have similar problems, suggesting that such problems could also be related to a system that is dedicated to attributing perceived events to self (the who system; Jeannerod, 1999, 2003). A number of recent neuroimaging studies of healthy individuals seem to support this idea (Decety & Chaminade, 2003; Farrer & Frith, 2002; Fink et al., 1999; Leube, Knoblich, Erb, & Kircher, 2003). Such a system might also have contributed to change detection in the present study.

To conclude, many movements are carried out unconsciously, and these movements also affect the sensitivity for detection of changes in visuomotor coupling. In a sense, the unconscious adjustment of movements conceals certain external influences affecting action. It could therefore be said that the conscious system is deceived about the amount of control it exerts. However, this sort of deception serves a good purpose: It helps to establish the high flexibility of visuomotor couplings that is needed for successful action.

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