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RESEARCH NOTE

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The use of visual feedback is independent of visual awareness: evidence from visual extinction

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Abstract Milner and Goodale (*The visual brain in action*, Oxford Press, 1995) made a distinction between vision for perception and vision for action. In contrast to perception, many action tasks have strict temporal constraints, which can only be met if the visual information is relayed directly to the motor system without first passing through a conscious decision making process. Milner and Goodale therefore predict that visual stimuli do not have to reach visual awareness in order to guide rapid motor responses. Online visual feedback provides a good example of visual information that is used under tight temporal constraints to guide rapid motor responses. Online visual feedback provides information about the position of the moving limb. This information can be used to improve the accuracy of our movements. If vision for action operates independently of visual awareness, visual feedback should be beneficial even if the subject is unaware of this information. We tested this prediction in a patient (V.E.) with left-sided visual extinction, a condition in which a visual stimulus typically fails to reach awareness if a second stimulus is presented simultaneously at a more rightward location. V.E. was asked to point towards a central target with his left hand. In some trials a light-emitting diode (LED) provided brief visual feedback from the moving hand. However, in the majority of trials, V.E. was unaware of this LED, due to his extinction. His performance was nevertheless significantly better when visual feedback was present, regardless of whether or not the information was available for verbal report. We conclude that visual awareness is not essential for the effective use of online visual feedback.

Keywords Pointing · Consciousness · Visuomotor control · Perception and action · Ventral and dorsal

Introduction

Milner and Goodale (1995) have argued for a model which distinguishes functionally between the two primary cortical visual streams. It is claimed that the ventral stream serves object recognition and conscious perception, and that the dorsal stream provides visual information for the guidance of action. Damage to the dorsal stream will thus lead to selective deficits in the visual guidance of action. One ability that is severely affected by a disruption of processing in the dorsal stream is the correction of movements online on the basis of new visual information. This is confirmed both by a study on a patient with bilateral posterior parietal cortex lesions (Pisella et al. 2000) and by a study using unilateral, repetitive transcranial magnetic stimulation over the same area (Desmurget et al. 1999). In both cases the deficit was restricted to an inability to update movement trajectories in response to a jump in target location in a pointing task.

Online visuomotor control is required whenever a change in the target or an error in the ongoing motor response is detected visually. In either case, the visual information must be processed sufficiently fast that corrective adjustments can be implemented before the motor response has been completed. For brief, rapid movements, it is assumed that the necessary visual processing can occur only if conscious decision processes are by-passed (Pisella et al. 2000). Therefore, in contrast to visual processing in the ventral stream, which leads to a conscious visual percept, visual processing in the dorsal stream may occur in the absence

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of awareness (Milner and Goodale 1995). We would therefore predict that online visuomotor control may be unaffected by a deficit of visual awareness.

One common neurological condition which leads to a selective deficit of visual awareness is visual extinction. Patients who suffer from visual extinction will typically fail to report brief visual stimulation in their contralesional hemifield if the ipsilateral field is stimulated simultaneously (Bender 1952). A large number of studies have found evidence of implicit processing of visual information in patients with visual extinction (see Driver 1996 and Driver and Vuilleumier 2001 for reviews). The tasks used in these studies were perceptual tasks, and the performance achieved was typically below the level which would be expected under conditions where the visual information enters awareness (e.g. Berti et al. 1994; Volpe et al. 1979). In contrast, in the case of an online visuomotor control task we would predict that it may be possible, in principle, to achieve the same level of performance without visual awareness as can be achieved when awareness is elicited.

To test this prediction, we tested a patient with left-sided visual extinction on an online visual feedback task. During an online visual feedback condition, subjects see the hand or finger that is involved in the manual response. Performance in this condition is contrasted with performance in a condition in which the hand/finger is invisible during the movement. Thereby the effect of the provided visual feedback information can be assessed (for a review see: Churchill et al. 2000). We arranged the task in such a way that our extinction patient would be unaware of the visual feedback from his left hand on a sub-total proportion of trials in which feedback was available. This allowed us to compare his performance in trials where he was aware of the visual feedback with trials where he was not. We predicted a significant and similar visual feedback effect for trials with and without awareness of the feedback information.

Methods

Subjects

Patient V.E. was a 76-year old, right-handed man who had sustained an ischaemic infarct in the territory of the right middle cerebral artery. One year later he was examined neurologically and specifically tested for visual field deficits and signs of unilateral neglect. His visual fields were confirmed to be full using a Tübingen Perimeter. At this time any signs of unilateral neglect, which had been reported in the acute stage, had been resolved as assessed by the Behavioural Inattention Test (Wilson et al. 1987). However, V.E. still showed clear signs of visual and tactile extinction to confrontation, and these extinction deficits were re-confirmed a few days prior to our experiments. V.E. showed no signs of paresis or other motor problems. Figure 1 shows a structural magnetic resonance imaging (MRI) scan of V.E.'s brain taken shortly before the present experiments. There is clear involvement of the right temporal lobe with sparing of the medial temporal and hippocampal structures. The anterio-inferior aspect of the right parietal lobe is also affected. There is slight damage to the anterior aspect of the right occipital lobe, but the majority of the occipital lobe is spared. In addition, there is ischaemic change to the cerebral white matter, bilaterally, but more pronounced on the right. However, the superior parts of the posterior parietal cortex: the so-called 'dorsal stream' (Culham and Kanwisher 2001; Connolly et al. 2003) appears to be unimpaired. Three healthy, male, right-handed subjects (aged 67–82 years) served as controls.

Apparatus

We recorded the subjects' movements with a movement registration device (Fa. Zebris, sampling frequency

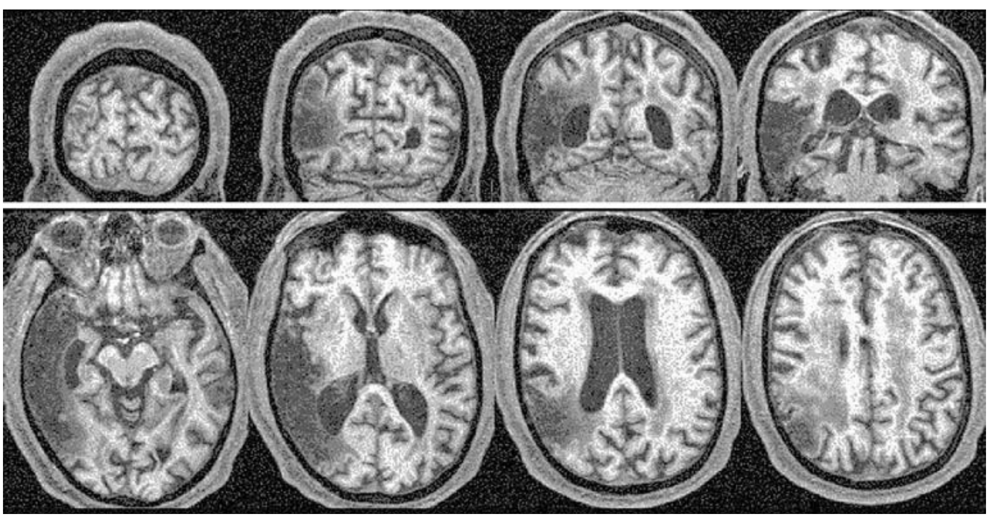

Fig. 1 MRI scan of patient V.E.'s brain, presented in coronal and axial sections, with the right hemisphere shown on *the left*

80 Hz, spatial resolution 0.1 mm) which uses ultrasonic signals to track the position of its markers. A single marker, attached to the index finger of the left hand, was used. The experiment was performed in darkness. LEDs on the table (*target-LEDs*) and an LED on the tip of the index finger (*finger-LED)* were used to present visual targets and to provide visual feedback respectively. Subjects sat in front of the table and used their left hand for the task. The start position of the hand was 20 cm to the left and anterior to the subject's body-midline, and also left to the position of the targets. The targets were 50 cm in front of the subjects' body, and 5 cm to the right or left of the body midline. The set-up is illustrated in Fig. 2a.

Methods and results for the pilot phase

During the pilot phase we examined patient V.E. to determine the optimal duration for the visual feedback information. Brief exposure durations will produce more reliable visual extinction but will also render the visual feedback information less effective. We therefore tried to determine the maximum duration at which visual extinction would still arise on a reasonably high proportion of trials. Since our final aim was to determine how visual extinction would affect the use of visual feedback in a pointing task, we also used a pointing task in the pilot phase. The procedures for this task are illustrated in Fig. 2b–d. A target LED was first presented, after one second the target-LED was turned off, simultaneously with a tone which prompted the subject to move towards the position of the target-LED. Immediately after the subject started to move (indicated by the release of the start button), either only the target-LED was turned on (*target-only trials*), or only the hand-LED was turned on (*hand-only trials*) or both the target and hand-LED were turned on (*target + hand trials*). Patient V.E. was asked to report, after he had completed the pointing movement, whether he had seen the target-LED alone, the hand-LED alone or both LEDs. We used blocks of 45 trials. Each block comprised 15 trials from each condition. The trials were presented in a randomized sequence. The exposure duration (i.e. duration for which the LEDs were turned on after the movement onset) was increased in steps of 100 ms from 300 ms to 700 ms from block 1 to block 5. The same blocks were then presented a second time in reverse order. In total, 450 trials with 30 trials for each condition and exposure duration were carried out.

V.E. never failed to report the target-LED or the hand-LED when only one LED was presented. However, when both LEDs were presented simultaneously he often reported only the target-LED, and missed the hand-LED which was to the left of his body-midline. This confirmed that V.E. showed reliable left-sided visual extinction in the pointing task and that the rate of extinction was modulated by the exposure duration (rate of extinction on target + hand trials: 100% at 300 ms; 83% at 400 ms; 77% at 500 ms; 37% at 600 ms; 6% at 700 ms). We decided to use an exposure duration of 500 ms, which in our experience was long enough to provide effective visual feedback information (Schenk et al. 2004), yet would still lead to visual extinction in a majority of the target + hand trials in the case of patient V.E.

Experimental procedures

The task for this experiment was similar to that used in the pilot phase except that no hand-only trials were employed. Trials were randomized and presented in four blocks of 40 trials each. An exposure duration (i.e. duration of LED-illumination during the hand movement) of 500 ms was used for all trials

As an additional manipulation, in two blocks of trials, we used prismatic glasses, inducing a rightward shift of 10° in the visually perceived position of the target. In the absence of visual information about the pointing hand (i.e. in the absence of visual feedback), subjects will point towards the visually perceived position of the target, and will therefore err to the right of the real target. However, if the hand is also visible during the movement, the subject may notice the aiming error, and can correct this error online (Jakobson and Goodale 1989). Accordingly, visual feedback has a pronounced effect in such a condition. This is in contrast to conditions without prismatic glasses where the effects of visual feedback are mostly small and are not always significant (Schenk et al. 2004). By using prismatic glasses, we can therefore expect to see significant improvements in performance when visual feedback is available. We compared the performance in the prismatic condition (block 2 and block 3) with a baseline condition (block 1) and a post-prismatic condition (block 4). It was expected that this design should enhance the chances of detecting evidence of the use of visual feedback, and also allow us to check the consistency of our results across different experimental conditions.

Data analysis

In some trials subjects started to move prior to the onset of the start signal. We repeated those trials where we suspected an early start, at the end of the block. During the offline analysis it turned out that early starts were more rare than expected, and therefore we ended up with more trials than intended (i.e. 160–170 trials per subject). Some kinematic traces were incomplete, and these traces had to be discarded (less than 5% of all trials). To filter the kinematic traces a non-parametric regression method using a low-pass filter with a bandwidth of 50 ms was applied (Marquardt and Mai 1994).

The results from each subject were analysed separately. In this type of analysis each subject represents the population of possible responses from which the observations are drawn, and each trial represents a case or

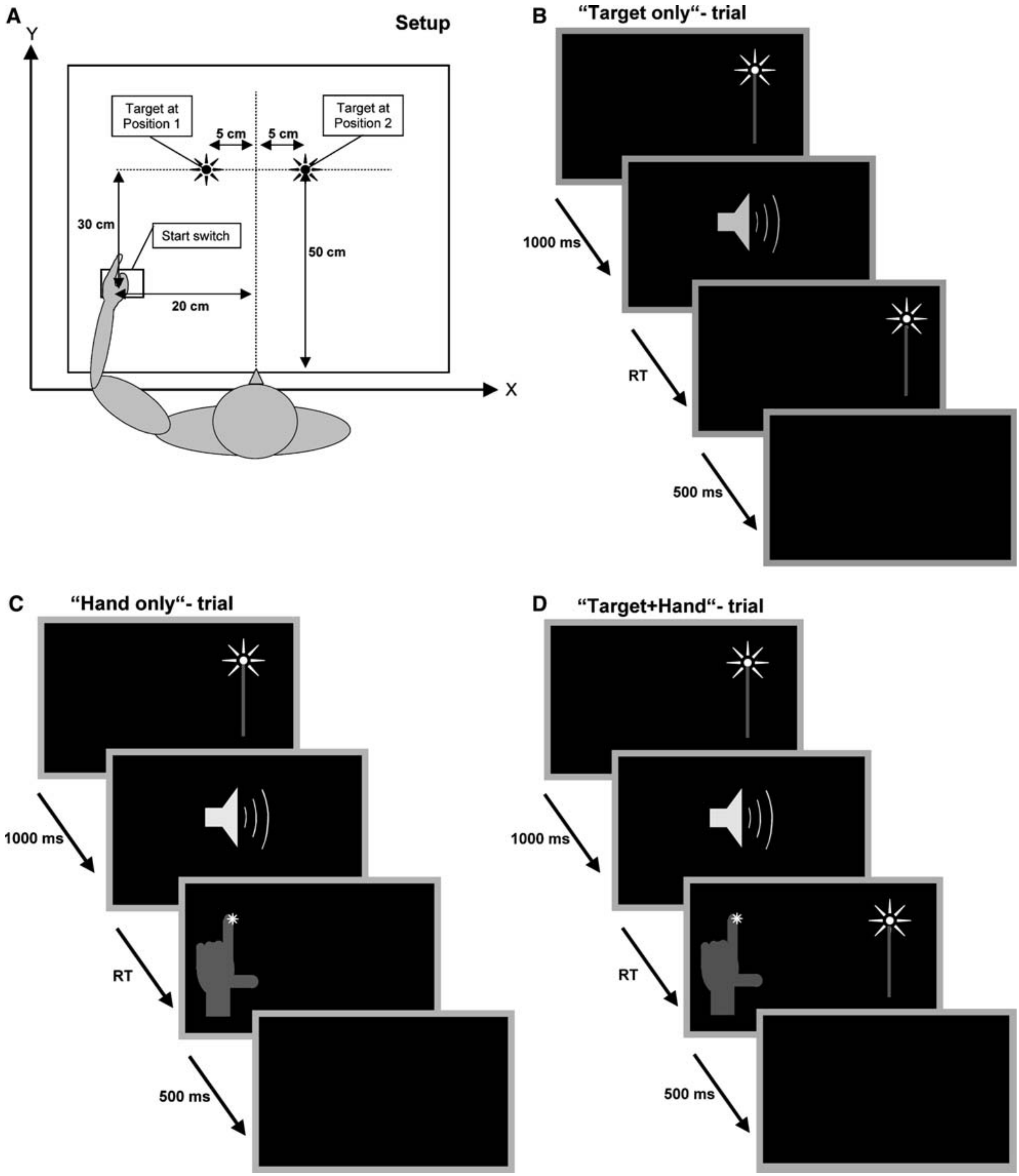

Fig. 2 Setup and experimental procedures. **a**. Illustration of the setup showing the two possible target positions, the starting position of the hand, and the dimension of the *xy* coordinate system, which was used for the computation of the accuracy measure (*xy*-error). Please note that the setup is not drawn according to scale. **b–d**. Illustration of the sequence of events in the target only (**b**), hand only (**c**) and target and hand (**d**) trials

observation. This approach is the conventional procedure adopted in almost all single-subject studies. Strictly speaking the observations in this case are not truly independent, since there may be sequential dependencies between trials. However, in our case the critical experimental conditions (i.e. with or without visual feedback) were randomly distributed across the sequence of trials, and thus it is not expected that inter-trial dependencies would have an effect on the outcome of the statistical test.

For each trial we determined the non-directional *xy-error* which corresponds to the distance between the movement endpoint and the target position in the horizontal plane. Additionally movement time (*MT*) and the peak velocity (*VMAX*) for the pointing response were also analysed. For each subject an ANOVA with the factors *condition* (*baseline*, *prismatic*, and *post-prismatic* condition) and *feedback* (*target-only/no visual feedback* versus *target + hand/with visual feedback*) was computed. Additional *t* tests were used to make a number of specific comparisons (see results).

In the case of V.E. a number of further analyses were carried out. Given that the position of the hand and the target might affect the degree of visual extinction, and thereby also how visual feedback information was used, we carried out a separate ANOVA which included the factor *target position*. Moreover, an additional accuracy measure was employed. Our primary measure for accuracy (*xy*-error) is non-directional, and therefore well suited to test the consistency of visual feedback effects across different experimental conditions. However, one might argue that we might thereby miss phase-specific effects of visual feedback and visual extinction, since it is expected that the horizontal direction of the error will switch at the transition from the prismatic to the post-prismatic phase. To assess this possibility we included in our analysis a further accuracy measure, namely the signed *horizontal error* (i.e. the difference between the horizontal position of the movement endpoint and the target).

Results

Control subjects

Verbal report

The control subjects reported both target and finger-LEDs correctly in all trials.

Accuracy (xy-error)

Visual feedback had a significant main effect on *xy*-error in all three control subjects (see Table 1). In the case of subject S2 and S3, a significant main effect of condition was also found indicating that the *xy*-error was elevated in the prismatic (S2) and post-prismatic (S3) conditions. A significant interaction between visual feedback and condition was observed only in subject S2. This interaction was related to the more pronounced feedback effect observed in the prismatic condition (see Fig. 3b). Most importantly significant visual feedback effects were obtained for all subjects in almost all conditions, the only exception being subject S2 who showed no significant feedback effect in the post-prismatic condition (see Fig. 3a–c).

Table 1 Effect of feedback and condition on accuracy (*xy*-error) in healthy subjects

Subject	Effect	df	*F*	*P*
S1	Feedback	1/159	23.98	<0.001*
	Condition	2/159	0.72	<0.488
	Feedback × condition	2/159	0.32	<0.721
S2	Feedback	1/161	63.0	<0.001*
	Condition	2/161	228.80	<0.001*
	Feedback × condition	2/161	17.83	<0.001*
S3	Feedback	1/166	14.22	<0.001*
	Condition	2/166	53.00	<0.001*
	Feedback × condition	2/166	0.67	<0.513

*Significant differences

Kinematic variables (MT/VMAX)

Neither movement time (MT) nor peak velocity (VMAX) of the pointing response was affected by any factor involving visual feedback (i.e. neither a main effect of factor feedback nor an interaction effect). This lack of a feedback effect on kinematic variables is slightly surprising given that other authors (for a review see: Churchill et al. 2000) reported faster responses in the presence of visual feedback. However, it should be noted that previous studies used a blocked design, which means that subjects knew in advance whether they could expect their hand to be seen or not. This means that subjects might have programmed their movements differently in those blocks of trials where they knew that feedback could be expected. In our study subjects did not know in advance whether online feedback was given or not, and thus anticipatory changes to the motor program for the pointing response were not possible. This might explain, why feedback did not have an effect on movement kinematics in our study.

The only factor which produced significant effects was the factor condition (see Table 2). However, as can be seen in Table 2, the effect of condition on movement speed and duration was not consistent across subjects. Depending on the subject, the fastest response could occur in any of the three conditions. It appears that the kinematic variables are as much affected by practise and fatigue as by the experimental conditions themselves.

Patient V.E

Verbal report

In the target-only trials patient V.E. always reported the target LED. In the target + hand trials, he missed the finger-LED in 65% of the trials. This extinction rate varied slightly across the different experimental conditions (70% during the pre-prismatic phase, 57% during the prismatic phase, 75% during the post-prismatic phase), but the effect was not significant ($\chi^2=2.52$; $P>0.05$). The reduced extinction rate in the prismatic condition probably reflects the fact that during the prismatic condition the visual percept of the hand is

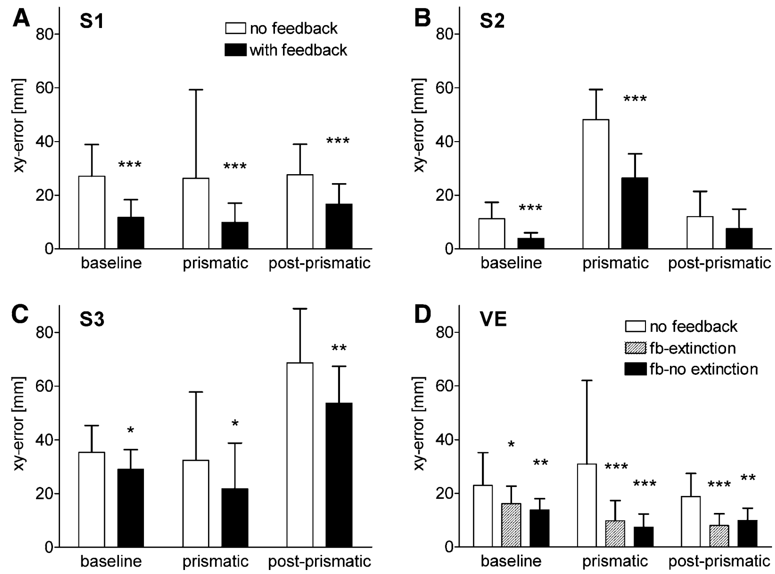

Fig. 3 Effect of visual feedback on pointing accuracy (*xy*-error) in three healthy subjects (**a–c**) and in patient V.E. (**d**). Pointing accuracy was measured by computing the distance between the *xy*-position of the movement endpoint and the *xy*-position of the target. This distance is called the *xy*-error, and is measured in mm. The *bar graphs* depict the mean (*bars*) and the standard deviation. The *open bars* show the results for the trials without visual feedback. The *black* bars show the results for the trials with visual feedback. In the case of patient V.E., the trials with visual feedback have been divided into those trials where the visual feedback information was extinguished (*black bars*) when compared to those where it was not extinguished (*grey bars*). The number of *stars above the bars* indicate the results from the *t* tests which compared the pointing accuracy with and without visual feedback (*no star*: $P>0.05$; $^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$). Please note that, in the case of patient V.E., trials in which the visual feedback was extinguished, and trials in which it was not both differed significantly from trials where no visual feedback was provided. The two types of visual feedback trials (i.e. with and without extinction) did not differ significantly from each other

shifted towards the right, making it less prone to left-sided visual extinction. A similar non-significant trend ($\chi^2=1.67$; $P>0.05$) was found for target position. The extinction rate for right targets was slightly lower (58%) than for left ones (71%).

Accuracy (xy-error, horizontal error)

The initial ANOVA which included the factor target position did not yield any significant effects of target position (neither main effect nor interaction effects). Results were therefore pooled across the two different target positions for all further analyses. To examine whether awareness of the visual feedback information was necessary for its effective use, we split the visual feedback trials into two groups depending on whether V.E. was aware (fb-no extinction) or unaware (fb-extinction). These trials were compared with each other and with the trials where no visual feedback was provided in a series of *t* tests. The results of those *t* tests are summarized in Table 3 (*xy*-error) and Table 4 (horizontal error). In all three conditions, V.E.'s performance was significantly better when visual feedback was provided. This was independent of his awareness of the visual feedback information. Moreover, in none of the conditions did we obtain a significant difference between trials with and without extinction. Figure 3d illustrates the distribution of *xy*-errors across conditions for patient V.E.

Table 2 Effect of condition on movement time (MT) and peak velocity (VMAX)

Subject	Condition			Baseline		Prismatic		Post-prismatic	
	df	*F*	*P*	Mean	SD	Mean	SD	Mean	SD
MT									
VE	2/164	6.93	< 0.001	714.36	63.07	703.64	91.08	757.70*	71.86
S1	2/159	21.38	< 0.001	485.19	57.89	552.02*	70.44	496.45	41.06
S2	2/161	69.67	< 0.001	795.01*	99.62	960.48*	80.63	1014.83*	98.25
S3	2/166	126.64	< 0.001	777.46*	87.34	607.86*	66.73	563.15*	50.60
VMAX									
VE	2/164	27.43	< 0.001	1023.61*	79.38	1126.12*	149.80	956.38*	122.97
S1	2/159	4.88	< 0.001	1616.30*	211.6	1733.80	207.05	1703.93	163.02
S2	2/161	37.87	< 0.001	1225.60*	238.24	1103.19*	149.08	906.93*	119.91
S3	2/166	1.82	> 0.05	1140.01	199.11	1196.96	186.64	1207.69	181.60

*Significant differences

Table 3 Effect of visual extinction on use of visual feedback in patient V.E.: *xy*-error

Condition	Comparison	*t*	df	*P*
Baseline	No fb versus fb-extinction	2.12	33	0.040*
	No fb versus fb-no extinction	2.80	24	0.009*
	fb-extinction versus fb-no extinction	0.812	19	0.345
Prismatic	No fb versus fb-extinction	4.11	62	0.001*
	No fb versus fb-no extinction	4.68	56	0.001*
	fb-extinction versus fb-no extinction	1.26	40	0.213
Post-prismatic	No fb versus fb- extinction	5.26	39	0.001*
	No fb versus fb-no extinction	3.45	27	0.003*
	fb-extinction versus fb-no extinction	0.888	22	0.400

fb visual feedback
*Significant differences

Table 4 Effect of visual extinction on use of visual feedback in patient V.E.: horizontal error

Condition	Comparison	*t*	df	*P*	Feedback and awareness	mean (mm)	SD
Baseline	No fb versus fb-extinction	−2.09	33	0.045*	No fb	−22.87	12.35
	No fb versus fb-no extinction	−2.80	24	0.009*	fb-extinction	−16.12	6.51
	fb-extinction versus fb-no extinction	−0.81	19	0.345	fb-no extinction	−13.75	4.21
Prismatic	No fb versus fb-extinction	2.61	62	0.012*	No fb	20.10	30.59
	No fb versus fb-no extinction	2.61	56	0.012*	fb-extinction	6.56	9.09
	fb-extinction versus fb-no extinction	−0.23	40	0.845	fb-no extinction	7.08	5.02
Post-prismatic	No fb versus fb-extinction	−2.30	39	0.028*	No fb	−14.92	14.36
	No fb versus fb-no extinction	−1.45	27	0.153*	fb-extinction	−7.51	4.98
	fb-extinction versus fb-no extinction	0.82	22	0.433	fb-no extinction	−9.52	5.20

fb visual feedback
*Significant differences

Kinematic variables (MT/VMAX)

With respect to the kinematic variables V.E.'s results again closely mirrored those of the control subjects. Feedback had no effect on MT or VMAX, whereas condition affected both MT and VMAX (see Table 2). The significant effect of condition was produced by the particularly slow response during the post-prismatic phase (Table 2). It is conceivable that this reduction in movement speed and increase in movement duration simply reflects the increasing fatigue towards the end of the experimental session. No feedback × condition interaction was found for any of the kinematic variables.

Discussion

We found that visual feedback can be used even if the feedback information does not enter visual awareness. In fact, in our patient, the effect of visual feedback was indistinguishable between conditions with and without awareness of the feedback information. This supports our hypothesis that online visuomotor control is independent of visual awareness.

It is interesting to compare our findings with earlier reports of implicit processing in patients with visual extinction. Most studies have used perceptual tasks, and found above-chance performance in conditions where patients were unaware of the visual stimulus (Driver 1996). However, the performance in the absence of visual awareness was inferior to the performance that would be expected if the visual stimulus were consciously perceived (Driver and Vuilleumier 2001). This is in contrast to our findings where performance with and without awareness of the visual feedback information appeared to be identical. This contrast perhaps suggests that visual awareness in perceptual tasks is crucial for fully normal performance, whereas visual awareness is dispensable in the case of online visuomotor control. Since online visuomotor control has been shown to be a dorsal-stream function (Desmurget et al. 1999; Pisella et al. 2000), our findings thereby suggest that visual processing in the dorsal stream is less dependent on visual awareness (Milner and Goodale 1995).

Further support for this distinction comes from an earlier study of our patient V.E. (McIntosh et al. 2004). In this study an obstacle avoidance task was used to examine the effect of visual extinction on visuomotor performance. It was found that the patient would veer away from obstacles which he did not report having seen. Although this task did not involve online motor corrections (since the movements were executed without visual feedback), there is nevertheless evidence to suggest that obstacle avoidance, like online visuomotor control, is a function of the dorsal pathway. This has been shown by Schindler et al. (2004) who found that patients with damage to dorsal stream areas were impaired in the obstacle avoidance task.

In conclusion, our findings provide an example to support Milner and Goodale's (1995) claim that visual processing in the dorsal stream is less dependent on visual awareness than in the ventral stream.

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