Limited conscious monitoring of motor performance in normal subjects

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(Received 10 June 1997; accepted 30 December 1997)

Abstract—Normal subjects traced sagittal lines on a graphic tablet using a stylus held in their right hand. The hand was hidden by a mirror in which they saw the lines projected from a computer screen. In normal trials, the line seen in the mirror exactly corresponded to the traced line. In perturbed trials, a bias was introduced by the computer, so that the line appeared to deviate in one direction (right or left) by a variable angle (1, 4, 6 or 09°). Subjects consistently displaced their hand in the opposite direction for producing a visually sagittal line. After each trial, they were asked in which direction they thought their hand had moved. In perturbed trials, they grossly underestimated the hand deviation. In addition, a post-hoc analysis revealed that one group of subjects misperceived the direction of their hand movement in the direction opposite to the perturbation (Group 0, including 8 Ss), whereas the other group gave responses in the correct direction (Group 2, including 4 Ss). In a second session using the same experimental paradigm, a motor response was asked for: subjects had to indicate the perceived direction of their hand during each trial by drawing a line with their eyes closed. Again, responses indicated a poor conscious monitoring of motor performance. These results suggest that normal subjects are not aware of signals generated by their own movements. © 1998 Elsevier Science Ltd. All rights reserved.

Key Words: voluntary movements; consciousness of action; vision; proprioception; efference copy.

Introduction

Many aspects of our own actions, even when performed intentionally, remain outside our awareness. This fact, of a limited access to consciousness of action, raises several interesting questions. First, what is the nature of the physiological signals, generated during an action, and used by the subject to monitor his own performance? Second, is it possible to dissociate, in the process of action generation, levels which can be accessed consciously from those which cannot? And finally, what are the implications of such a limitation for understanding the frequent delusions of action and perturbations of agency observed in pathological conditions?

It is known from the literature that normal subjects are poorly aware of many aspects of their own actions. For example, if a target briskly changes its location during the ocular saccade that precedes a pointing movement toward that target, subjects may remain unaware of the displacement (they see only one, stationary target); yet, they correctly point at the final target location [3, 26]. Goodale et al. [9] reported a similar pointing experiment where the target occasionally made jumps of several degrees, unnoticed by the subjects. They found that the subjects were nonetheless able to adjust the trajectory of their moving hand to the target. Interestingly, no additional time was needed to produce the correction, and no secondary movement was observed, suggesting that the visual signals related to the target shift were used without delay for adjusting the trajectory. These experiments suggest that generating a motor response to a stimulus and building a perceptual experience of that same stimulus do not rely on the same mechanisms. Indeed, the two processes can be temporally dissociated: in an experiment where subjects were tracking by hand an unexpectedly moving target, the change in their hand trajectory occurred as early as 100 ms following the target jump, whereas the vocal signal by which they reported their awareness of the jump was not observed until more than 300 ms later [1].

These results raise the point of how and to what extent subjects can consciously access their own motor performance. It seems logical to assume that in order for an agent to recognize his/her own actions and attribute them to their correct source, he/she must be able to detect
signals generated by these actions at some point during their preparation or their execution. Only a very few experiments have examined this point. The Libet et al. [19, 20] findings suggest that intentions to carry out voluntary action are generated unconsciously. These authors instructed subjects to perform simple hand movements ad libitum and to report the instant (Wa: wanting arousal) at which they became aware of “wanting to move”. In addition, readiness potentials were recorded from the subjects’ skull. The time Wa was found to lag the onset of readiness potentials by about 350 ms. In Libet’s terms, “the brain ‘decides’ to initiate or, at least, to prepare to initiate the act before there is any reportable subjective awareness that such a decision has taken place” [20].

The present experiment was designed to investigate further the degree of accuracy of subjective reports about one’s own movements, and to determine which signals can possibly be used for monitoring voluntary actions. To this aim, we adapted a situation previously described by Nielsen [12], where subjects were unknowingly shown an alien hand in exact visual coincidence with their own hand. This situation allows creating conflicts between what subjects actually do with their (invisible) hand and what they see from the displacements of the visible (alien) hand. In our experiment subjects were instructed to draw lines in the sagittal direction. A bias was randomly introduced in the visual display of the lines, such that they had to deviate from the sagittal direction in order to fulfill the instruction. We found that the subjects largely ignored the actual movements that their hand had performed.

Methods

Subjects

Thirteen healthy subjects (7 males, 6 females) volunteered for this study. Their age ranged between 21 and 43 years (mean 28 ± 0.23). All subjects were right handed according to the Edinburgh inventory [24], they had no personal or familial neuropsychiatric antecedents, and had normal visual acuity. They were unaware of the purpose of the experiment.

Apparatus

The experimental device consisted of a 30 × 45 cm graphic tablet placed on a regular table, and connected to a computer. The computer screen was placed horizontally at 62 cm above the graphic tablet. A circular mirror (35 cm in diameter) was placed horizontally halfway between the screen and the tablet (Fig. 1). The subjects sat comfortably on a chair facing the table and held in their right hand a pen stylus connected to the graphic tablet computer. Their head was free to move. The right hand was placed on the tablet, below the mirror. When tracing a line on the tablet, the subjects could see a red line appearing through the mirror on the computer screen in exact coincidence with the displacements of the tip of the stylus on the tablet.

The output of the graphic tablet was processed by the computer using a simple algorithm for adding a linear directional bias of varying direction (right or left) and amplitude (2, 5, 7, and 10°). When the bias was set, e.g. at 10° to the right, a line traced in the sagittal direction on the tablet appeared to the subject to deviate to the right at an angle of 10° (Fig. 2).

Procedure

At the beginning of each trial, the subjects placed the stylus tip on a starting position located on the tablet close to the body midline. They were instructed to reach a yellow target (3 × 4 mm) located on the sagittal axis at 22 cm from the starting position. They had to draw a continuous line as straight as possible and at an even speed, keeping the hand in contact with the tablet. The duration of a trial was limited to 5 s. After this delay, the screen was blanked and a new trial started.

After 10 practice trials, the experiment was run in blocks of 18 trials for each amplitude of the bias (4 blocks, 72 trials per subject). In each given block six trials involved no bias (unperturbed trials), six involved a bias directed to the left and six to the right (perturbed trials). These three conditions were randomized. When the bias was introduced, it appeared at a prescribed distance (57 mm) from the starting position (see Fig. 2).

Subjects performed two sessions of 72 trials. The two sessions were identical, except for the question that was asked to the subjects at the end of each trial. In Session I, subjects were asked to give a verbal estimate of their motor performance. They were shown a card with lines drawn at different angles from a starting point. These lines were numbered from 1 to 13. Lines 1–6 deviated to the left with respect to the axis of the card, lines 8–13, to the right. The line numbered 7 was aligned with the card axis (see the insert in Fig. 3). The question to the subjects was: “According to your own impression, which line corresponds to the actual trajectory drawn by your hand?”. The verbal response had to be given by reading the corresponding number on the card.

In Session II, subjects were asked to give a motor response. At the end of each trial they were instructed to close their eyes, their right hand holding the stylus was placed by the experimenter on the tablet at the starting position and they were asked to draw a line in the direction corresponding to what they had perceived during the trial. Before Session II, subjects underwent a small block of five trials where they were instructed, with their eyes closed, to draw a line in the straight ahead direction. The data from these trials were used as a reference for processing the data of Session II.

Data analysis

For both Sessions I and II, the lines traced by the subjects during each trial were stored and subsequently analysed for their duration, terminal accuracy and linearity. Duration was measured at the nearest 15 ms (sampling rate of the digital tablet, 70 Hz). Terminal accuracy was measured as the deviation of the line with respect to the position of the target. The line was considered linear when it remained within ±10 mm from the sagittal axis.

For Session I, the verbal responses for each subject were analysed. The numerical values of each response were added and averaged for each degree and direction of bias. The values for the unperturbed trials (0° ‘bias’) were pooled across all blocks.

For Session II, the motor responses were analysed by measuring, for each subject, the angle of the line connecting the starting position and the last point of the response with respect to the line corresponding to the straight ahead direction (as defined above).

P. Fourmeret and M. Jeannerod/Limited conscious monitoring
Analysis of variance (ANOVA) and Scheffé’s post-hoc tests were used to study the perturbation effects on verbal and motor responses.

Results

Overall performance

All subjects correctly performed the task, i.e., when a bias was present, they moved their hand in the opposite direction, so that the lines appeared on the screen to be directed toward the target. Only a few trials had to be rejected on the basis of departure from the limits assigned for linearity of the tracings. In the overall sample, 0.1% of trials were rejected from the unperturbed trials and 2.3% from the perturbed trials. As a rule, the lines traced by the subjects ended within the target for the 2° and 7° biases, or close to it (average error, 2 mm) for the 10° bias.

Movement duration was shorter for unperturbed trials (2368 ms, SD = ±408) than for perturbed trials (3090 ms, SD = ±619). This difference, however, did not reach statistical significance [F(7.96) = 0.319, P < 0.94]. No relation was found between movement duration and degree of bias [r = 0.06, r(92) = 0.67, P < 0.5].

Session I: verbal responses

The mean response for the unperturbed trials averaged across all subjects was 7.02 (SD = ±0.223; SE = ±0.061). Responses for the perturbed trials were also clustered around the value of 7, indicating that subjects had not clearly perceived that their hand actually deviated from the sagittal (straight ahead) direction.
Fig. 2. Graphic representation of one perturbed trial. Heavy line: visual reafference as seen by the subject. Dashed line: direction (right) and amplitude (10°) of bias. Light line: trajectory of the hand-held stylus on the tablet, unseen by the subject. Note direction opposite to the bias. Scale on left shows distance between starting point and target (222 mm) and onset of bias (at 57 mm from starting point).

Fig. 3. Verbal responses of the two groups of subjects. Numbers in ordinate refer to the orientation of the lines on the response card shown to the subjects (insert on right).

The statistical analysis revealed no effect of amplitude and direction of bias on verbal responses when responses from all subjects were considered. By contrast, the interaction between the factor subject and direction of bias was highly significant. This result (Table 1, verbal responses) suggests that the verbal responses differed from subject to subject.

A post-hoc analysis (comparisons of means by the Scheffe’s test) was thus performed, which confirmed that the subjects could be split into two groups. Nine subjects (Group 1) gave responses in the same direction as the bias (e.g. they gave values corresponding to the left side of the card if the bias was to the left), whereas four subjects (Group 2) behaved in the opposite way.

Figure 3 displays the averaged verbal responses as a function of the degree and direction of bias in subjects of the two groups. The opposite relationship between the verbal responses and the direction of bias is clearly visible.
A simple linear regression was computed to evaluate this relationship. Correlation coefficients were highly significant for both groups (Table 2). Despite this fact, however, the net values estimated by the subjects deviated only little from the sagittal value of 7. For the largest bias (18°) the average response was around ±2.5°, i.e., one fourth of the actual deviation.

**Session II: motor responses**

One subject had to be excluded from this session at the data processing stage, because of technical problems during the recording.

The subjective straight ahead direction was measured for each subject using the five trials at the beginning of the session. In accordance with previous data from the literature [16], a small leftward bias was found in all subjects (mean = −0.95; SD = ±2.911; SE = ±0.840). For each subject, the individual bias was subtracted from the value of the mean motor response.

Motor responses retained for data processing amounted to 98.7%. The mean direction of motor responses across the overall sample showed a tendency for the subjects to trace lines close to the straight ahead direction. For the unperturbed trials, the mean direction was −0.98° (SD = ±3.876; SE = ±1.119). For the perturbed trials, it was −0.99° (SD = ±0.370; SE = ±1.177).

The ANOVA revealed an effect of the factors subjects and direction of bias on the motor responses (see Table 1, motor responses). The same post-hoc analysis as described above was performed. It resulted in the same separation into two groups and with the same subjects as in Session I.

The correlation study (Table 2) revealed that subjects from Group 1 (N=9) did not show any relationship between their motor responses and the value of bias (Fig. 4, left). By contrast, subjects from Group 2 (N=3) showed such a correlation: they tended to give motor responses in a direction opposite to the bias, as they did for their verbal responses in Session I (Fig. 4, right). However, for the three subjects of Group 2 who passed the two sessions, no correlation was found between motor and verbal responses (r = 0.26, F(1,22) = 1.71, P > 0.203).

**Discussion**

The main outcome of this study is that normal subjects appear to be poorly, if at all, aware of the details of their motor performance and to be unable to correctly monitor, consciously, the signals generated by their own movements.

In our experiments, several categories of signals were in principle available to the subjects. A first category was represented by sensory signals, including visual signals related to the apparent direction of the movement, and kinesthetic signals related to the actual direction of the arm. A second category was represented by putative “endogenous” signals, possibly arising from the motor commands generated by the subject. During the unperturbed trials, all signals provided coherent information: the visually perceived and the kinesthetically felt directions of the movement were superimposed, and this information was congruent with the subjects’ intentions. During the perturbed trials, by contrast, the visual signals were in conflict with the others. In order for the line to appear straight ahead, the subjects had to deviate their hand path by the same amount as the amount of the bias, and in the opposite direction. Thus while the visual signals indicated the straight ahead direction, the kinesthetic signals indicated a different direction. Similarly, the signals derived from the motor command sent to the arm to trace a line straight ahead were in disharmony with the kinesthetic signals generated by this same movement.

When asked to verbally indicate in which direction their hand had moved, all subjects tended to indicate a direction close to the straight ahead direction. In other

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**Table 1. Summary of the results of the two-way ANOVAs related to the main analysis**

<table>
<thead>
<tr>
<th></th>
<th>Amplitude (A)</th>
<th>Direction (D)</th>
<th>Subject (S)</th>
<th>A × D</th>
<th>A × S</th>
<th>D × S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal responses</td>
<td>F(3,100) = 0.18</td>
<td>F(1,102) = 2.97</td>
<td>F(12,91) = 0.66</td>
<td>F(3,96) = 0.70</td>
<td>F(36,52) = 0.14</td>
<td>F(12,78) = 17.28</td>
</tr>
<tr>
<td>Motor responses</td>
<td>F(3,92) = 0.04</td>
<td>F(1,94) = 1.56</td>
<td>F(11,84) = 23.56</td>
<td>F(3,88) = 0.07</td>
<td>F(33,48) = 0.53</td>
<td>F(1,72) = 5.28</td>
</tr>
</tbody>
</table>

Significant P values appear in bold characters.

**Table 2. Results of correlation study between the responses and the deviation by a simple linear regression analysis after the separation of the subjects into two groups**

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal responses</td>
<td>F(1,70) = 201.41</td>
<td>F(1,30) = 54.45</td>
</tr>
<tr>
<td></td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
</tr>
<tr>
<td></td>
<td>r = 0.86</td>
<td>r = −0.80</td>
</tr>
<tr>
<td>Motor responses</td>
<td>F(1,70) = 0.26</td>
<td>F(1,22) = 5.31</td>
</tr>
<tr>
<td></td>
<td>P &gt; 0.60</td>
<td>P &lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>r = −0.06</td>
<td>r = −0.45</td>
</tr>
</tbody>
</table>
words, they tended to grossly underestimate the deviation of their hand trajectory with respect to the sagittal axis. This point will be specifically discussed below. A post hoc analysis of the data, however, showed that individual responses in fact tended to covary with the amplitude and direction of the bias. Responses of subjects from Group 2, to start with, were in the correct direction, i.e., in the direction in which the hand had effectively moved. It can be inferred from this result that subjects in this group were able to consciously monitor their kinesthetic signals, in spite of contradictory evidence from the other signals. Subjects from Group 1, however, gave responses in the direction opposite to their actual hand movement. The type of signal monitored by these subjects can only be discussed tentatively. A likely possibility is that, although they discarded the kinesthetic information, they paid greater attention to endogenous signals related to the central level of movement generation. In the perturbed condition, where the hand had to be “pulled” away from the bias, the subjects may have monitored the resistance exerted by this external force against their effort to move in the desired direction.

At the moment, there is no obvious explanation available for the existence of the two types of responses corresponding to Groups 1 and 2, respectively. It is worth remembering, however, the diverging interpretations given to the effects produced, in a situation similar to ours, by artificially produced “conflicts” between the seen position and the felt position of the hand (the so-called visuomotor or “prism” adaptation paradigm). Held and his group had favoured an interpretation of adaptation based on implicit monitoring of central mismatch signals resulting from a comparison between the motor command and the corresponding reafference [12]. This mechanism would provide a basis for the responses given by our Group 1 subjects. On the contrary, Harris had postulated that the felt position of the arm exposed to the conflict was changed so as to coincide with the seen position [11], a mechanism accounting for the strategy used by Group 2 subjects when asked to make conscious judgements about their motor performance.

In spite of the weak covariation of the responses with the direction of the bias, the main finding reported here is the low gain of the responses given by the subjects in both groups, with respect to the amplitude of the perturbation at the input of the system. Several possible explanations can be considered. First, it can be conjectured that, because the visual effect on the screen was compatible with the desired action, our subjects tended to largely ignore the other, discrepant action-related signals. This explanation refers to the well known dominance of visual information over other information from other modalities [11]. Another possibility is that the weakness of the responses might reflect the weakness of the action-related signals themselves. This seems an unlikely explanation, however: proprioceptive signals are permanently used for improving movement control, as can be inferred from the devastating effects of somesthetic deafferentation. In addition, the fact that due corrections were produced in the experiment, in order to draw sagittal lines in spite of the bias, shows that the relevant signals were indeed monitored by the visuomotor apparatus.

A third possible explanation for the weakness of the responses is that, although proprioceptive and internally generated action-related signals correctly operated at an automatic and unconscious level, they were not available for conscious monitoring. It is known that conscious position sense, to which kinesthesia greatly contributes,
rapidly degrades after a new position has been assumed [28]. It is also noteworthy that internally generated action-related signals are barely perceived consciously. It is only in situations where the desired effect cannot be obtained that subjects feel their “efforts of will”. One example is the overestimation of weights lifted by a limb weakened by fatigue or experimentally produced partial paralysis [8, 22]. A recent longitudinal observation on a patient with a pure motor hemiplegia fully confirms these findings [25]. The weight matching task was used to measure the degree of effort produced to move the paralysed arm during the four month post-stroke recovery: the subject had to determine, by moving his unaffected arm against a weight, the amount that corresponded to the effort needed to produce a test movement with his affected arm. The change in the estimated degree of effort exactly mirrored the regain in muscular strength.

The signal monitored by the subjects in such circumstances is likely to arise from the increased motor command needed to recruit more muscular units than normally required for overcoming the same resistance. It is uncertain, however, whether their conscious responses relate to the amount of effort they have to produce or to the intensity of the resistance they have to overcome. In our experiment, the use of each of these cues should have produced opposite responses: responses based on the amount of effort should have been in the direction opposite to the bias, whereas responses based on the resistance should have been in the same direction. The fact that Group I subjects gave the latter type of response suggests that their responses were based on the resistance rather than on the effort.

Session II was performed in order to disentangle these possibilities. In asking the subjects to relate the trajectory along which their hand had moved, we thought that they could copy some internal model of their movement, based on kinesthetic or internally generated signals. The outcome of this session, in showing an almost complete lack of deviation of the hand trajectory from the sagittal direction, including after trials where a large bias had been introduced, reinforces the idea that the signals generated by a previous movement are indeed poorly accessible to conscious monitoring. One could tentatively infer from this result that the role of action-related signals is limited to movement execution and that they are stored in a working memory, which is only active during execution and is rapidly erased after movement completion.

These results raise important questions when considering the putative role of action-related signals in the behavioural context. In the classical models of the corollary discharge and the efference copy, the activity of a central comparator was thought to reflect the degree of match between internally generated commands and the sensory signals resulting from the corresponding action: whether the efference copy and the sensory signals concorded or not was the cue to attribute the observed effects to an endogenous or an exogenous origin, respectively [13, 15, 27]. A similar mechanism might be used for labeling actions and referring them to their viridical source [7, 17, 18]. More recently, PET experiments have allowed a more direct access to the process of action representation. Cognitive states like preparing, imagining or observing actions have been investigated. The major contribution of these experiments was to show that the patterns of brain activity, although they differ from one state to another, involve many common areas. Actions performed by the subject or observed from other people involve overlapping areas [2, 10]. It is therefore logical to assume that the activity from non-overlapping areas represent sufficient cues for attributing an action to its cause; but it is also logical to assume that the activity of areas which are shared by several modalities of representations may create ambiguities for making the proper judgement. The results of the present experiment suggest that this distinction relies on signals which are poorly accessible to conscious awareness and that the differences between an intention originating from the self and an intention originating from someone else must be quite subtle.

The notion of a central monitoring (conscious or not) of efferent signals related to motor intentions provides a tentative conceptual framework for describing the pathological functioning of motor representations. A defect in this monitoring process has been proposed as a possible basis for a neuropsychological theory of schizophrenia [4, 5]. In the domain of motor actions, this theory predicts that schizophrenic patients should no longer be able to monitor efferent signals resulting from their intentions and should therefore have defective functioning of their motor representations, namely the process of comparison and should therefore have defective functioning of their motor representations, namely the process of comparison between the efferent and the reafferent signals should no longer be possible [4]. Accordingly, it has been shown that schizophrenic patients have difficulties in generating motor corrections. Malenka et al. [21] found that these subjects, in the absence of visual feedback from their movement, were unable to correct the direction of a tracking movement when the target displacement was reversed. Similarly, Frith and Done [6], also using a motor task with error correction, noticed that psychotic patients with experiences of alien control of their thoughts were less likely to make corrections than other types of psychotic patients. The failure of the “intention monitor” [6, 7] thus explains why schizophrenics may not be able to keep track of whether an action was produced as the result of a prior intention, or whether it was triggered by an external stimulus. Experiments with psychotic subjects are now going on, using the same situation as described here, to determine their pattern of responses.

Acknowledgements—We thank Brigitte Delouis and Christian Urquizur for their technical assistance in writing the perturbation program. The work was supported by GIS Sciences de la Cognition, Paris. Pierre Fourneret is supported by a fellowship awarded jointly by the CNRS and the Hospices Civils de Lyon.
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