

THE timing of two simultaneous responses to one single visual event, namely the sudden subjective expansion of a real object occurring at the onset of a reaching movement, was measured in normal subjects. The motor response was represented by the earliest sign of correction in trajectory of the movement. The subjective report was represented by a vocal utterance that the subjects were instructed to emit when they became aware of the change in appearance of the object. The subjective report lagged the motor response by 150 ms. Control experiments ruled out a possible interference between the two responses. It is concluded that this temporal dissociation reflects a duality of neural pathways involved in processing object-related information.

Key words: Awareness, Visual perception, Sensorimotor coordination, Levels of processing, Temporal dissociation

Measuring time to awareness

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Introduction

How long does it take us to become aware of external events? When we generate a movement in response to a visual stimulus, is our perceptual experience of that stimulus synchronous with our motor response? And, if not, can the temporal dissociation between the two be measured? Although these seem difficult questions, they relate to fundamental and still poorly explored, aspects of neuroscience. In recent years, however, data have accumulated, suggesting awareness as a separate attribute of brain activity, unrelated to sensorimotor functioning, and pertaining to a distinct set of neural mechanisms. An illustration of this point is found in the study of brain damaged patients. In cases of prosopagnosia, for example, it can be shown that, although the patients have lost access to the overt, conscious process of face recognition, the covert neural operations for identifying faces are in fact preserved. Single case studies have shown that normal autonomic responses can be recorded in these patients when a familiar face (which they cannot recognize) is presented to them.^{1,2} This dissociation, created by brain lesions, between overt and covert responses to the same events, suggests that different modalities of processing external events are operating simultaneously, the modality that leads to awareness being one of them.³

Similar phenomena can also be observed in normal subjects. Suppose an experimental situation where the visual target to which a subject is responding by a pointing movement is briskly displaced. It has been shown that, if the target displacement is triggered during the ocular saccade that accompanies the pointing movement, the subjects remain unaware of the displacement; yet, they can point correctly at the final target location.⁴ Goodale *et al.*⁵ described a similar

experiment where the target made jumps of several degrees, unnoticed by the subjects. They found that subjects were nonetheless able to adjust the trajectory of their moving hand in order to reach the target. Interestingly no additional time was needed for producing 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. More recently, Paulignan *et al.*⁶ systematically investigated this ability to produce fast corrections. They found that it takes no more than 100 ms to initiate a corrective movement in response to a sudden change in the position of a target-object triggered at the onset of a reaching movement. The overall duration of the reaching movement was increased by a corresponding amount of 100 ms. Furthermore, the subjects participating in these experiments consistently reported the impression that they 'saw' the object changing position near the time when they were about to grasp it, that is, much later than the actual occurrence of the object displacement.

Castiello *et al.*⁷ using the same experimental situation, undertook the task of measuring the temporal dissociation between these two responses to the same event: the motor correction and the subjective report about the object displacement. An estimate of the time to awareness was obtained by instructing the subjects to emit a vocal utterance as soon as they saw the object jumping. The results were interesting in several respects. First, the short time to initiate the correction, as found by Paulignan *et al.*,⁶ was confirmed. Secondly, the vocal utterance was found to be systematically delayed from the motor correction by about 315 ms, thus supporting objectively the subject's impression of seeing the object jumping later than it actually did and validating the choice of a vocal response as the index of awareness.

However, this large temporal dissociation was not always found. When the subject had to reach for an object which appeared suddenly but was not subsequently displaced (hence requiring no motor correction), the time to start the movement and the awareness time were within the same range: it took 320 ms to start moving the hand, while it took 380 ms to signal the presence of the object vocally. In such cases, the subject's perceptual experience was that of seeing the object appear at the same time as movement onset.

It may be interesting to speculate on why a perceptible temporal dissociation between the motor and the vocal responses appeared only in the correction situation, and not in the normal situation. One possible explanation of this phenomenon may be found in the difference in the time needed to produce the motor response in the two situations. While in the normal situation, where the object remained stationary, the visuomotor reaction time was within the usual range of 300 ms, in the correction situation, this time was reduced down to

about 100 ms. It may be that, in the latter case, the strong time pressure under which the correction was executed gated the activation of fast visuomotor pathways. At any rate, this difference suggests that the time needed to generate a motor response to a visual event may change as a function of the task in which the response is given, whereas, by contrast, the time to signal awareness would remain invariant. We decided to test this hypothesis by using a similar situation involving motor corrections but where the experimental variable was a change in appearance of the object. In this situation, described by Paulignan *et al.*,⁸ the onset of the reaching movement triggered a change in the size of the object, without modifying its spatial position. This visual perturbation therefore affected the neural commands related to distal finger movements which are likely to be more complex and more cortically organized than those for accommodating changes in position. Our prediction was that the time needed for a motor correction following a change in object size would come closer to the time needed to become aware of this perturbation.

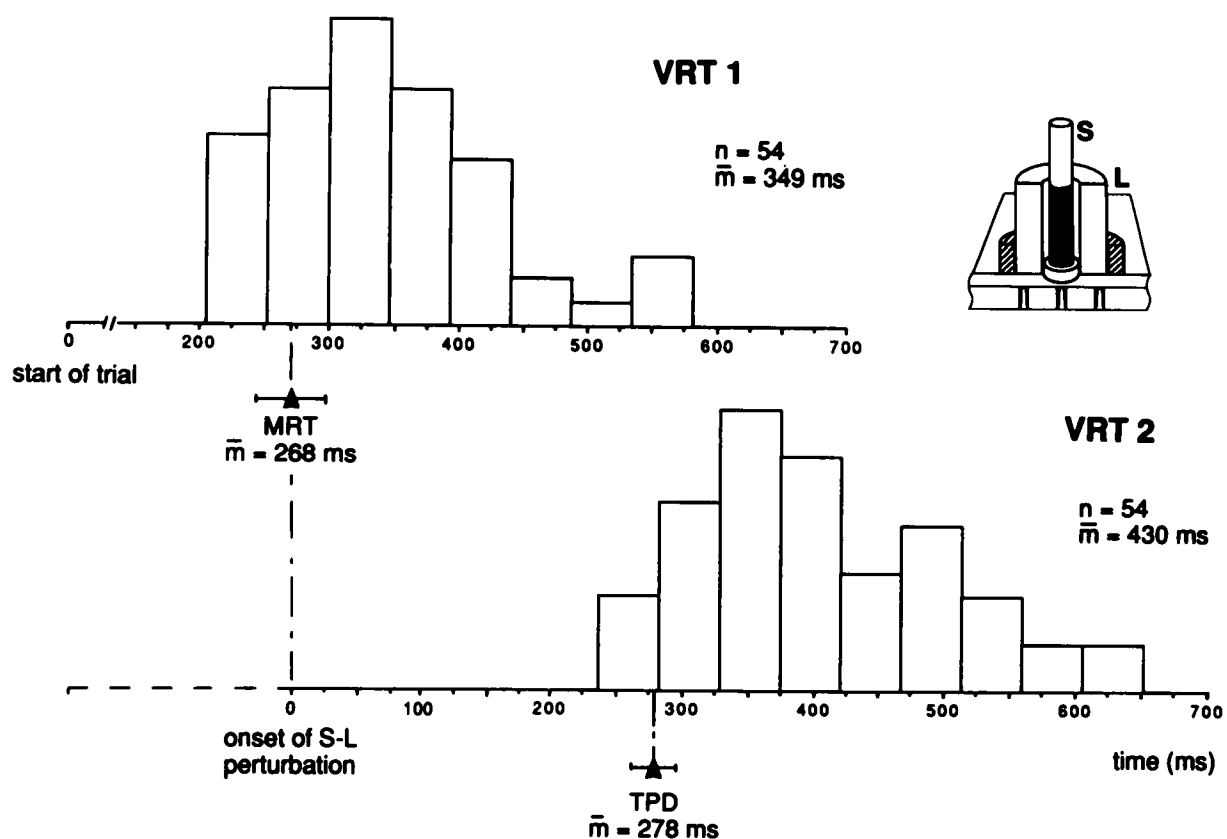


FIG. 1. Distribution of vocal reaction times in small-to-large (S-L) perturbed trials in the six subjects. Upper row, vocal reaction times (VRT1) to presentation of the first (small) object. Presentation of the object determines the start of the trial. Compare the mean value of VRT1s (349 ms) with the mean value of motor reaction times (MRT, 268 ms, horizontal bar shows s.d.). Lower row, vocal reaction times (VRT2) to small-to-large perturbations. Onset of perturbations is produced by movements toward the small object. Compare the mean value of VRT2s (430 ms) with the mean value of time to peak deceleration of the transport component (TPD, 278 ms, horizontal bar shows s.d.). In this experiment, TPD represents the first recordable sign of motor correction in response to the perturbation. The vocal response, signalling subject awareness, lags the motor response by about 150 ms. Insert, apparatus used for producing size perturbations. In the experiment illustrated here, the small dowel (S) is illuminated first and the light is shifted to the large dowel (L) at the onset of the movement, hence producing apparent expansion of the object.

Materials and Methods

Six normal subjects were requested to reach, grasp and lift with their right hand, one of two concentric dowels made of translucent plastic material and placed in front of them at 35 cm. The inner dowel (the 'small' dowel) was 10 cm high and 1.5 cm in diameter. It stood inside the 'large' dowel (6 cm high and 6 cm in diameter). Computer controlled LEDs placed below the dowels were used to illuminate either one of the dowels (Fig. 1, insert). Illumination of one dowel was the signal for the subjects to start their movement. Following a few practice trials, a block of 100 trials was run. Each trial started with illumination of either the small or the large dowel. In 80 trials the dowel remained illuminated until completion of the trial (S-control trials for the small dowel, L-control trials for the large one). In the other 20 trials, which were interleaved with the control trials, the onset of the movement triggered a shift of the illumination, either from the small to the large dowel (S-L perturbed trials) or from the large to the small dowel (L-S perturbed trials). The shift in illumination (and the corresponding change in dowel size) was produced by a switch released by the onset of the reaching movement. In addition, subjects were instructed to emit a vocal response (Tah!) each time they saw a change in illumination. This vocal signal was recorded through a microphone and transformed into an analog pulse sampled at 200 Hz. Vocal reaction times (VRTs) were measured between illumination of the dowel and onset of the vocal signal.

Arm movements were recorded using a Selspot system. An infrared emitting diode (IRED) was placed at the level of the wrist, for monitoring the transport component of the movement. IREDs were also placed at the tips of the thumb and the index finger for monitoring the grasp component. The thumb to index finger distance was used as an index for the size of the grip during prehension. IREDs position was sampled at 250 Hz by a digital camera. A second order dual-pass filter (high-pass cutoff frequency, 8 Hz) was used for data processing. The tangential velocity was computed after filtering.

Acceleration was derived by differentiating the velocity data. Movement times, kinematic variable of wrist and finger trajectories and vocal reaction times were compared in trials where no perturbation in object size occurred, and in perturbed trials. Data obtained in the S-control trials served as a reference for studying the S-L perturbed trials, and data obtained in the L-control trials, for the L-S perturbed trials.

Results

Movement time (MT) was increased in the perturbed trials: MT was 67 ms longer in S-L trials than in S-controls, and 43 ms longer in L-S trials than in L-controls. Kinematic analysis of the wrist trajectory revealed that both the time to peak acceleration and the time to peak velocity kept the same duration in both control and perturbed trials. The first sign of motor correction found in this experiment was the earlier occurrence, in perturbed trials, of the peak deceleration (TPD) of the transport component; TPD occurred 56 ms earlier in S-L trials than in S-controls, and 26 ms earlier in L-S trials than in L-controls (Table 1). All the above-mentioned time values are significant at the 0.005 level (paired *t* test). As a consequence of both the increase in MT and the decrease in TPD, the low velocity phase at the end of the movement was lengthened. The duration of this phase increased by more than 25% in perturbed trials. In addition, the pattern of finger grip formation was modified, especially in S-L trials. In this case, the anticipatory closure of the finger grip, planned for the small dowel, was interrupted and finger movements were reverted in order to accommodate for the size of the large dowel. This reversal occurred around 330 ms following the perturbation.

Vocal reaction times following illumination of the first dowel (VRT1) were very similar in both control and perturbed trials. Vocal reaction times following the change in size in perturbed trials (VRT2) were 430 ms on average (Table 1). Figure 1 shows the distribution of vocal reaction times during S-L perturbed

Table 1. Mean values (and s.d.s) of reaction times and relevant kinematic parameters in the main and control experiments.

	Main experiment					C1	C2	C3	C4	
	MRT	MT	TPD	VRT1	VRT2				VRT1	VRT2
S	276 (55)	549 (59)	334 (46)	338 (70)		313 (28)	327 (54)		353 (73)	
L	281 (48)	545 (70)	314 (39)	345 (73)		307 (35)	332 (59)		349 (52)	
S-L	268 (57)	616 (87)	278 (23)	349 (87)	430 (82)	290 (35)		423 (63)	338 (62)	431 (51)
L-S	280 (50)	558 (80)	288 (14)	358 (77)	429 (51)	269 (28)		420 (58)	341 (36)	415 (33)

MRT, motor reaction time; MT, movement time; TPD, time to peak deceleration of the transport (wrist) movement; VRT1, vocal reaction time to presentation of the first target; VRT2, vocal reaction time to change in target size. S, L, control trials directed at small and large objects, respectively; S-L, L-S, perturbed small-to-large and large-to-small trials, respectively. C1-C4, control experiments.

trials in all subjects. In this figure, the distribution of VRT1s can be compared with the mean motor reaction time (which corresponds to the onset of the arm movement), and the distribution of VRT2s can be compared with both the onset of the visual perturbation, and the onset of the motor correction (TPD).

Control experiments were run with the same subjects, for testing the degree of interference between the simultaneous motor and vocal tasks used in the main experiment. The sequence of the main and the control experiments was counterbalanced between subjects in order to prevent sequential effects. Control experiment C1 involved performing the motor task alone, without voicing; C2 was limited to emitting a vocal response to the first illuminated dowel only (VRT1) without moving the hand; C3 involved performing the motor task and emitting a vocal response only to the change in dowel size (VRT2); C4 involved performing the vocal task alone. The results (Table 1, C1–C4) revealed no significant differences in the relevant parameters between the control experiments and the main experiment (paired *t* tests).

Discussion

Several important results arise from the present series of experiments. First, the motor correction in response to the change in object size occurred relatively late in the movement time. A good way to estimate the minimum amount of time needed for detecting the change in size and initiating the motor correction is to compare the timing of the kinematic landmarks in control and perturbed trials. The first noticeable difference was the time to peak deceleration which occurred about 40 ms earlier on average in perturbed trials, thus giving an estimate of time to correction of about 280 ms. This contrasts with the much shorter time of correction reported for changes in object position (about 100 ms^{6,7}). Comparison between the two experiments seems justified by the fact that 2 of the 6 present subjects participated in both, with very different times to correction for changes in object position and in object size. Slower motor response to size perturbations may relate to the higher degree of complexity of the visuomotor pathways for controlling distal movements. This pathway involves processing the

visual attributes of objects which are normally used for object identification and recognition. Such processing, which is likely to involve cortical mechanisms (e.g., see reference 9), would be time consuming, and would be compatible with a correction delay of nearly 300 ms. By contrast, as outlined above, the pathway for processing spatial localization and controlling direction of reaching movements would be simpler and have a shorter time constant.

The second important result reported here was that vocal responses from which the subject's awareness of change in object size was inferred occurred consistently more than 400 ms after the onset of perturbation (430 ms in the main experiment, 415–431 ms in control experiments). This is very close to the value of 420 ms reported elsewhere by Castiello *et al.*⁷ for conscious detection of changes in object position. In their experiment, the motor correction began around 105 ms and the temporal difference between the motor and the vocal responses was in the range of 315 ms. In the present case, the temporal difference between motor and vocal responses was in the range of 150 ms only.

Conclusion

The fact that the delay for subjective awareness of visual stimulus remains invariant, whereas the time to the motor response can be modulated as a function of the type of stimulus, or as a function of the task in which the subject is involved, reveals that the neural pathways leading to awareness are distinct from those involved in sensorimotor processing. The present paradigm of fast motor corrections, if applied to patients with localized brain lesions, might be a powerful tool for identifying these pathways.

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