



Dissociation between “where” and “how” judgements of one’s own motor performance in a video-controlled reaching task

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Abstract

The aim of the present study is to show that the sensorimotor system makes a differential use of visual and internal (proprioception and efferent copy) signals when evaluating either the spatial or the dynamical components of our own motor response carried out under a remote visual feedback. Subjects were required to monitor target-directed pointings from the images furnished by a video camera overhanging the workspace. By rotating the camera, the orientation of the movement perceived on the screen was either changed by 45° (visual bias) or maintained in conformity with the actual trajectory (0°). In either condition, after completing twenty pointings, participants had to evaluate their visuomotor performance in two non visual testing: They were both asked to reach the target in a single movement (evaluation of “how to reach the target”), and to evaluate the mapping of the spatial layout where they acted (evaluations of “where the starting position was and, what movement direction was”). Results revealed that though motor performance in the 45° conditions was adapted to the visuomotor conflict, participants’ evaluation of the spatial aspect of the performance was affected by the biased visual information. A different pattern was revealed for the evaluation of “how” the target was reached which was not affected by the visual bias. Thus, it is suggested that segregated processing of visual and kinesthetic information occurs depending upon the dimension of the performance that is judged. Visual information prevails when identifying the spatial context of a motor act whereas proprioception and/or efferent copy related signals are privileged when evaluating the dynamical component of the response.

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The production of goal-directed movements requires an accurate estimation of target and effector locations within the workspace. While several sensory systems (e.g., vision and proprioception) may contribute to specify arm-to-target spatial relationship, the way the sensorimotor system integrates the various sources of spatial information still remains an open issue. This is particularly the case for evaluating effector configuration, for which vision and proprioception may work simultaneously and furnish virtually similar spatial information.

Previous works on vision-proprioception interaction have highlighted a general tendency toward the prevalence of

visual information when vision and proprioception are in conflict in, position matching task [11] or in visuomotor performance [7,12]. In the latter situation, participants wore wedge-prism spectacles dissociating visual and proprioceptive signals about arm location and were instructed to produce pointing movements toward a target. Results showed that when the hand and the target were both visible prior to movement onset, participants used the viewed (displaced) position of the hand to determine the arm-to-target relation, thereby producing spatially accurate movement. Masking the hand before movement initiation resulted in spatial error in the direction of the optical deviation. These two results are expected only if one assumes that vision plays a crucial role in the processing of hand and target location. In the same vein, using a virtual visual feedback, Goodbody and Wolpert [6] observed that when decoupling the actual and the visually

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perceived hand in a horizontal midsagittal pointing task, participants located the target according to the biased visual hand only. Though convincing, this idea of a unimodal coding of the hand and the target has been challenged by other experiments. In a movement production experiment Rossetti et al. [13] showed that displacing electively the visual feedback of the initial hand position and leaving the visual location of the target unbiased resulted in spatial error in a direction opposite to the visual shift. Though the hand was viewed when estimating the position of the target, the magnitude of the errors concurred perfectly with a view considering a balanced contribution of visual and proprioceptive signals related to the hand. In addition, van Beers et al. [14,15] revisited the notion of a given modality prevalence and showed that the multimodal specification of arm posture may actually be dependent on the spatial dimension considered. Using an optimal integration model, they reported that visual and proprioceptive signals about the hand position are weighted with direction-dependent weights in such a way that the use of the available information is optimized. Thus controversial data exist concerning the sensory information used to code arm-to-target spatial relationship in a reaching task and the influence of visual signals seems to depend on the constraint imposed by the experimental context. This is indeed what is noticeable when comparing the spatial characteristics resulting from the evaluation of one's own motor performance with those of actual motor production. In a video-controlled reaching task, for instance, using a vertical video-monitor for the indirect control of horizontal pointings, Ferrel et al. [2] noticed that when changing the scale of the visual display individuals had the strong illusory sensation of performing movements of different amplitudes though the actual distance was kept constant. Such bias in the subjective evaluation resulting from the dominance of visual information was also described in other experimental contexts. For instance, Fournier and Jeannerod [3] asked subjects to trace straight lines toward a target visible on a computer-screen. Direct vision of the arm was precluded and participants had a real-time feedback of their line tracing on the screen. In some of the trials, whereas subjects actually traced straight lines, an experimental manipulation modified the orientation of the tracing so that it appeared rotated (up to 10°). Though subjects achieved the desired goal of drawing a straight line by making deviant movements, the perception of their own motor performance grossly underestimated the effective deviation. These two last studies thus confirm – the preponderance of visual information in the evaluation of one's own motor performance and, – the poor conscious awareness of internal signals generated by one's own movement (proprioception and efferent-copy related signals). In addition, turning to the specific role of visual signals, it was shown that visual information is used differently according to the purpose of the behaviour, i.e., perceiving or acting [10]. This is indeed what suggested studies relating to the influence of visual illusion on spatial processing. With the Ebbinghaus-Titchener size-contrast illusion for instance, Aglioti et al. [1] reported that

the size of a target disk surrounded by an annulus of large or small disks was more influenced by the visual context in a perceptual judgement task than in an actual grasping task. Such dissociation between the processing of visual information for acting or for perceptual categorisation was confirmed with other illusory configurations (e.g., the Müller-Lyer illusion [4] and the vertical–horizontal illusion [16]). But the existence of a differential processing of visual information for either perceiving or for effective visuomotor control does not include that one would favour internal action-related information when required to evaluate the dynamical properties of our own previous visuomotor performance. In other words, it is possible that visual information prevails when evaluating the spatial components of a motor response (“where” the movement was performed) but not when evaluating the dynamical component of the response (“how” to reach the target). With the latter, proprioception and/or efferent copy related signals might suffice to fulfil the evaluation task, particularly when these signals and vision are discrepant. The present research intends at testing the accuracy of the perception of one's own motor performance when dissociating the spatial and motor aspects of the evaluation in a video-controlled pointing task. Participants had to perform pointing movements from visual information displayed on a vertical video-monitor while acting on a horizontal surface. In presence of a rotation of the visual display (45°), the perceived trajectory does not match the actual hand trajectory and an adaptation to the directional bias is required. Thus, visual and proprioceptive feedbacks are no longer spatially related and the role of visual information when evaluating the spatial (“where”) or the motor (“how”) aspects of the task can be studied. We did so in a pointing task requiring adaptation to a visual rotation (45°) by asking fourteen right-handed subjects (11 females, 3 males, age range 18–26 years, naïve of the purpose of the experiment) to provide after the completion of a set of pointings an estimation of previous hand starting location and movement direction, and a movement reproduction (motor estimation of previous performance). Visual bias was expected to be more influential when evaluating hand location and movement direction than when evaluating the dynamical components through a reproduction of previously produced movements.

Participants were sat facing a video monitor ($0.4\text{ m} \times 0.4\text{ m}$) located approximately 0.85 m from the head, their position was adjusted so that the eye's level pointed to the centre of the screen. Participants performed three-dimensional pointings to a mid-sagittal target ($\varnothing = 23\text{ mm}$) disposed on the table at a distance of 0.25 m from the starting point ($\varnothing = 10\text{ mm}$). Direct vision of the workspace was prevented by an occluder and a Sony video camera placed 0.95 m recorded the arm displacement (1:1 ratio between physical and visual distance). The camera was fitted on a calibrated holder allowing to control 1—the rotation in a plane parallel to the table and 2—the confusion of the centre of rotation with the middle of the workspace. Participants carried out two sets of 20 pointings in two exper-

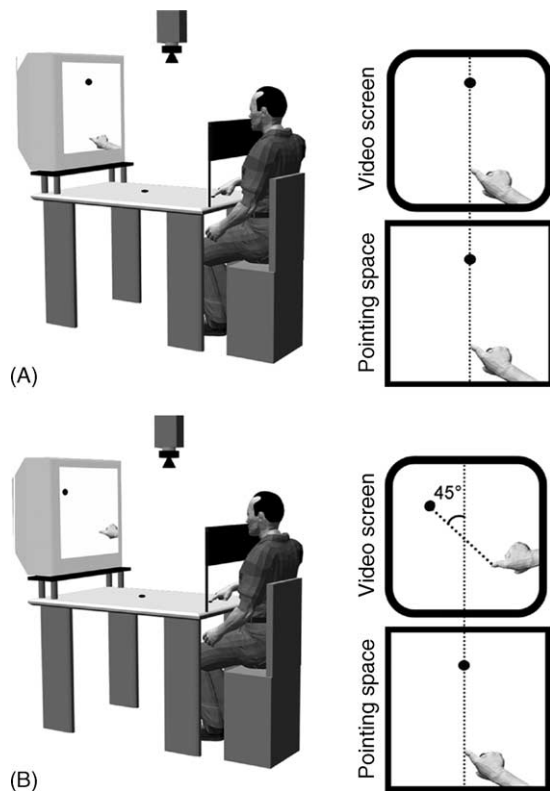


Fig. 1. Schematic view of the experimental setup. (A) 0° condition: the directional mapping between screen images and actual pointing space was unperturbed. (B) 45° condition: target and hand position, as viewed on the screen, were rotated by 45° with respect to the actual pointing space.

imental conditions of visual feedback. In the 0° condition, the visual hand-to-target gap was aligned with the actual gap (see Fig. 1A). In the 45° condition, the camera was rotated by 45° clockwise so that the hand and the target appeared on the screen as displaced in opposite direction (see Fig. 1B). The order of presentation of the two conditions of visual feedback (45° or 0°) was counterbalanced across subjects, with a pause of few minutes between each condition. Participants were instructed to produce the pointings as fast as possible but to necessarily reach the target with accuracy. Immediately after completion of the 20th trial, whatever the conditions (45° or 0°), participants were submitted to two counterbalanced non-visual evaluation tasks using either the right or left hand (ipsilateral—Ipsi, or contralateral—Contra, between-subjects conditions). In the movement reproduction (MR task), after being rapidly replaced on the starting position, they were asked to reach for the target in a single movement. In the spatial evaluation task (SE) subjects were asked to point to the initial hand location and to trace on the table the direction of the movement they carried out. It is to note that the delay between the two evaluation tasks was limited (less than 1 s). The x , y , z movements of an ultra-sound emitting diode placed upon the index fingertip was recorded at 100 Hz (spatial accuracy = 0.1 mm) with a movement registration system (ZEBRIS[®], Isny, Germany). Data were then processed under MATLAB 6.5

(The Mathworks[®]). Positional data were filtered using a second-order Butterworth dual-pass filter (cut-off frequency: 10 Hz). Movement onset was defined as the time at which the index finger tangential velocity first exceeded 3 cm/s. The end of the movement was defined as the first time the index finger was within 1 cm of the centre of the target and its speed was less than 3 cm/s.

In order to quantify visuomotor adaptation to the decorrelated visual-kinaesthetic feedback we analysed for each trial 1—the movement direction at first velocity peak [9], 2—the movement time and 3—the global appearance of the velocity profiles. Two two-way analyses of variance (ANOVA) were performed on initial movement direction (IMD) and movement time with repeated measures on the trial number (1–20) and on the condition of rotation of the visual feedback (45° versus 0°). For the evaluation of the perception of one's own motor performance, we computed 1—for MR the Angular Error (the angle between the 'veridical starting position-to-target' vector and the 'starting position-to-movement endpoint vector'—A_Er in degrees), and 2—for SE the location of the starting position evaluation and the direction of the evaluated movement with respect to a sagittal axis (the angle between the 'veridical starting position-to-target' vector and the 'evaluated starting position-to-evaluated endpoint vector'—A_Ee in degrees).

Results concerning movement adaptation to the decorrelated visual-kinaesthetic feedback showed that, at completion of the set of trials, the spatial-temporal performance in the 45° condition has reached a plateau that is comparable to the performance observed at the same stage in the 0° condition (see Fig. 2A). Temporal data indeed showed that whereas MT in the first trial was about two times longer in the 45° condition ($2875 \text{ ms} \pm 1738$) than in the 0° condition ($1444 \text{ ms} \pm 422$), movement duration in the 45° condition monotonically decreased as a function of the trial. Fisher's least significant difference post hoc comparisons showed that MTs in both 0° and 45° conditions were not significantly different from the 8th trial up to the 20th. Furthermore, whatever the conditions of rotation of the visual feedback (45° or 0°), velocity profiles obtained in the 20th trials evidenced a comparable bell-shaped monophasic appearance. In addition, though movement paths in the first trial of the 45° condition were inflexed leftward (in the direction of the visual bias) and trajectories in the first trial of the 0° condition were inflexed rightward, subjects adopted a straighter path as subjects completed the set of pointings in both conditions (for the 45° condition: 1st trial mean IMD = $39.7^\circ \pm 8.6$; 20th trial mean IMD = $1.6^\circ \pm 6$ and for the 0° condition 1st trial mean IMD = $-19.1^\circ \pm 7.2$; 20th trial mean IMD = $-5.8^\circ \pm 3$). Thus motor performance in the two visual feedback conditions can be considered as comparable with respect to spatial and kinematic parameters.

Fig. 2B shows mean A_Er obtained in the MR task. The comparison between 45° and 0° conditions evidenced significant differences ($t_{13} = 3.75$, $p < 0.01$) for the overall testing

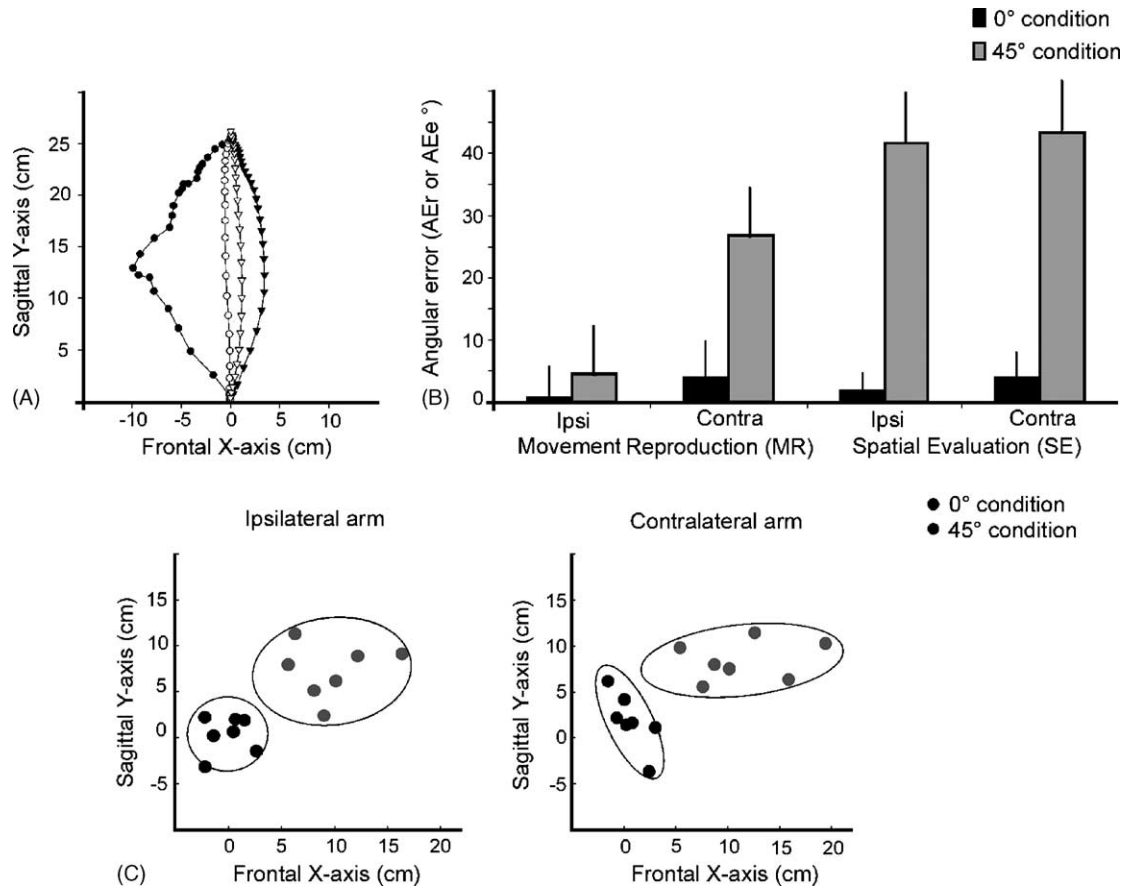


Fig. 2. Results in movement production, movement reproduction (MR) and spatial evaluation (SE) tasks. (A) Mean normalized trajectories (at 50 evenly spaced points) for the 1st (filled dots) and 20th trials (hollow dots) in the 45° (circles) and 0° conditions (triangles). (B) Mean angular error (AER in degrees) in the MR task and mean direction of the evaluated movement (AEe in degrees) in the SE task. (C) Individual performances in the evaluation of the location of the starting position in the spatial evaluation task as a function of the limb used (Ipsi and Contra between subject conditions) and the orientation of the movement perceived on the screen (45° and 0° within-subject conditions). The origin (0, 0) figures the veridical hand starting position used for every trial, axes are in cm and 99% confidence ellipses are superimposed onto the data points.

(i.e., whatever the arm used), for data in the contralateral arm condition ($t_6 = 7.46$, $p < 0.01$), but not for the ipsilateral arm condition ($t_6 = 1$, $p = 0.35$). Mean AER in each condition (45° versus 0° and ipsilateral versus contralateral arm) was tested against a reference norm of 0° (veridical direction leading to the target). Differences for 45°-Ipsi (mean = $4.71^\circ \pm 7.7$), 0°-Ipsi (mean = $0.28^\circ \pm 5$) and 0°-Contra (mean = $3.85^\circ \pm 6.6$) conditions were all not significant (all post hoc comparisons = ns) whereas mean AER for the 45°-Contra condition (mean = $26.8^\circ \pm 8.1$) was significantly different from the 0° norm ($t_6 = 8.74$, $p < 0.01$). In addition the 95% confidence intervals computed for 45°-Ipsi [-2.4 ; 11.8], 0°-Ipsi [-4.4 ; 4.9] and 0°-Contra conditions [-2.3 ; 10] all encompassed the 0° norm. Differently, the 95% confidence interval calculated for the 45°-Contra condition excluded the 0° norm [19.3 ; 34.3].

Fig. 2B illustrates the mean AEe evidenced by individuals in the SE task. As concerns the comparisons between 45° and 0° conditions, we found a significant difference for the overall testing ($t_{13} = 17.1$, $p < 0.01$), for the contralateral arm condition ($t_6 = 11$, $p < 0.01$) and for the ipsilateral arm condition

($t_6 = 12.3$, $p < 0.01$). Mean AEe in each condition (45° versus 0° and Ipsi versus Contra) was tested against a reference norm of 0° (veridical direction of the movement in the adaptation phase). Differences for 0°-Ipsi (mean = $1.5^\circ \pm 2.9$) and 0°-Contra (mean = $3.6^\circ \pm 4.2$) conditions were not significant ($p = 0.22$ and $p = 0.06$, respectively) whereas mean AEe for the 45°-Contra (mean = $43.1^\circ \pm 9.1$) and 45°-Ipsi (mean = $41.4^\circ \pm 8.6$) conditions were significantly different from the 0° direction norm (both $ps < 0.01$). In addition the 95% confidence intervals computed for the 0°-Ipsi [-1.1 ; 4.1] and 0°-Contra conditions [-0.2 ; 7.5] encompass the 0° direction norm. Similarly, 95% intervals calculated for the 45°-Ipsi and 45°-Contra conditions include 45° — respectively [33.5 ; 49.4] and [34.7 ; 51.5]. Results concerning individuals' evaluated starting position in the SE task are presented in Fig. 2C. We note that evaluations in the 45° condition are translated to the right (in conformity with the viewed displaced starting position on the display), whereas evaluations for the 0° condition lie closer to the veridical starting position (0, 0). These observations are consistent with a statistical analysis. As concerns the compar-

isons between 45° and 0° conditions, we found significant differences for the overall testing (x -coordinates $t_{13} = 8.15$, $p < 0.01$, y -coordinates $t_{13} = 6.85$, $p < 0.01$), for the Contra condition (x -coordinates: $t_6 = 5.44$, $p < 0.01$; y -coordinates: $t_6 = 4.66$, $p < 0.01$), and for the Ipsi condition (x -coordinates: $t_6 = 5.73$, $p < 0.01$; y -coordinates: $t_6 = 4.7$, $p < 0.01$). Mean x and y evaluated positions in each condition (45° versus 0° and Ipsi versus Contra) were tested against a reference norm of ($x = y = 0$, i.e., the position of the veridical hand starting position). All four comparisons for the 0° condition were not significant (all $ps > 0.20$) whereas all comparisons for the 45° condition were significantly different from 0 (all $ps < 0.01$). In addition the 95% confidence intervals computed for x -coordinates in the 45° condition for Ipsi [6.2; 13.3] and Contra [6.7; 15.8] conditions both include 8.83 cm (magnitude of the visual rightward displacement of the hand while on starting position). In contrast, 95% confidence intervals calculated for y -coordinates in the 45° condition do not include 3.67 cm (magnitude of the visual vertical displacement). As shown by the calculated confidence interval for the evaluated hand position along the sagittal (y -axis), participants overestimated the hand location in the 45° condition: Ipsi [4.3; 9.9] and Contra [6.35; 10.2] but not in the 0° condition [−1.6; 2.3] and Contra [−1.3; 4.5], respectively.

In the present study we investigated the accuracy of the perception of one's own motor performance when dissociating the spatial and motor aspects of the evaluation in a video-controlled pointing task. Using a remote-controlled pointing situation in which vision and proprioception signals were discrepant (visual rotation of 45°) we found dissociation in the influence of the visual signals in two non-visual evaluations of previous sensorimotor performance. When evaluating the dynamical aspects of the performance (i.e., in the MR task) with the same arm as in motor production, judgments conformed to the adapted motor production. Differently when the motor reproduction involved the contralateral arm, we noticed an influence of the visually perceived position of the target. As concerns the evaluation of the spatial aspects of the performance (i.e., the SE task), we noted that it was influenced to a great extent by the biased visual feedback, whatever the upper-limb used.

It is thus suggested that in such decorrelated situation action appears to be represented in two independent formats relying on a separate use of afferent sensory/efferent copy information. It is as if cognitive processing included processing of the most (usually) efficient and reliable information in order to carry out a judgement of one's own action. When evaluating the dynamical aspect of the motor performance ("how" to reach the target) judgments involved internal and unbiased movement information originating from proprioception and/or efferent copy signals. These descriptors of past actions are unaffected by contextual information (rotated visual feedback in the present experiment) and their processing lead to unbiased judgements. A parallel can be drawn between such separated perception of different movement-related properties (either dynamical or spatial aspects) and

Humphreys and Riddoch's finding [8]. These authors show that while a patient with unilateral neglect (patient MP) was capable of object-directed pointings when the description of the target-object was associated to an action, he remained unable to reach the same object when it was designed by its colour or its name. An opposite pattern was found in two other neglect patients. This outcome was interpreted as suggesting that the perception of motor and spatial properties of the same object does not rely on similar sensory information processing. Nevertheless, such optimized selection of the relevant sensorimotor information reaches a limit when participants placed in the 45° condition are forced to evaluate the dynamical aspects of the movement using the left "untrained" arm (Contra condition): In the absence of available internal information about the movement, an influence of visual signals appear. In this case, subjects complete the MR task in processing the visual spatial information about the target position. Our results further extend Fournieret and Jeannerod's conclusion [3] stating that, when required to elaborate spatial estimations of their own previous performance, subjects were poorly aware of signals generated by their own movements and conformed to the (biased) visual information. The present results suggest that when reproducing one's own movement (i.e., evaluating "how" to reach the target) one utilizes the information about the dynamical properties of previous motor production. A different pattern emerges when participants have to evaluate the spatial aspects of their motor production ("where the movement was performed"): Judgements in the SE task clearly involve the extensive processing of memorized visual information that usually best describes the spatial components of the workspace.

We propose that when judging one's own motor performance, intrinsic (proprioception and/or efferent copy related signals) or extrinsic (visual) information are electively processed depending upon the dimension of the performance that is evaluated (spatial or dynamical aspects). This interpretation seems to fit well with the segregated motor representations postulated by Dixon and Glover in their planning-control model of illusion effect on action [5]. These authors indeed suppose the existence of separated representations of the planning and the on-line control of action. We may then suppose that evaluating the dynamical dimension of a movement (i.e., the MR task) would appeal to a representation of movement control whereas the evaluation of the spatial aspects of action (i.e., the SE task) would rely on a representation of the planning processes carried out under biased visuomotor conditions.

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