Weight judgment
The discrimination capacity of a deafferented subject

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Summary
A weight discrimination study was undertaken to test (i) the capacity of controls and a deafferented subject (deprived of large sensory myelinated fibres from nose down), to discriminate weights with and without vision; (ii) the capacities of observers to discriminate weights while watching the deafferented and control subjects' lifting movements; (iii) the contribution of supplementary sources of sensory information (e.g. vestibular afferents) to the deafferented subject's discrimination capacity. With vision, G.L.'s liminal discrimination of weights was similar to that of the controls. In contrast, precluding vision impaired massively, but not completely, G.L.'s discrimination capacity, so emphasizing the importance of visual kinaesthetic cues in G.L. and incidentally the importance of large myelinated sensory function in weight discrimination in controls. Kinematics recordings of G.L.'s lifting movements with vision revealed a significant correlation between weight and peak velocity of the lifting movement. This reflects a specific strategy used by G.L. to generate movements, allowing her to judge the weight of a lifted object visually. Peak velocity rather than amplitude of movement appears to be the main cue for G.L. since there was a lack of correlation between amplitude and weight lifted. For controls, none of the correlations (weight versus amplitude or weight versus velocity) was significant, whether vision was available or not. When watching G.L.'s lifting performance, external observers were able to use similar cues to establish their judgments, but they were far less accurate in doing so when watching control subjects. This suggests that controls were using a strategy different from G.L.'s. Without vision, a residual discrimination capacity was observed for the heavier weights in G.L. Perception of the lightest weight disappeared after a mechanical stabilization of the head, suggesting the likely contribution of vestibular signals. Therefore, for G.L., a patient completely devoid of neck and limb proprioception our results limit the role a sense of effort or residual somatic afferents to the discrimination of the heavier weights.

Keywords: proprioception; kinaesthetic visual cues; sense of effort; weight discrimination; deafferentation

Abbreviations: DT = discrimination threshold; LED = light emitting diode; PSE = point of subjective equality

Introduction
Four mechanisms have been proposed to account for our capacity to evaluate the weights of lifted objects. One is based upon signals derived from cutaneous mechanoreceptors, relying on either the passive pressure of an object on the skin or the friction forces exerted by the active pressure of the grasping fingers opposing the slippage of the lifted object (Johansson and Westling, 1987; Johansson, 1991).

A second sensory mechanism involves proprioceptive signals derived from muscular or tendinous mechanoreceptors or joint receptors measuring the contractile force used to hold the object (Matthews, 1982). It is generally recognized that adding muscular kinesthesia to tactile cues greatly enhances the capacity to discriminate weights (Gandevia and McCloskey, 1977; Weber, 1834/1978).

Moreover, a third source of information, the sense of effort [also called sensation of innervation (Wundt, 1874; Helmholtz, 1925), corollary discharge (Sperry, 1950) and 'efferenz' copie (von Holiest, 1954)] could independently or jointly contribute to the perception of our own movement and consequently to weight discrimination (McCloskey et al.,...
1974, 1983; Gandevia and McCloskey, 1978). According to McCloskey et al. (1983), the sense of effort constitutes a centrifugal mechanism, relying on outgoing or motor discharges and reflecting the perceptual effect of retroactive signals of motor commands directly derived within the CNS through internal loops. It evokes sensations of various kinds. Such a mechanism does not require rejection of conventional peripherally arising sensory inputs as having a major role. Moreover, McCloskey et al. (1983) hypothesized that the matching of an efferent copy and proprioceptive reafferents might facilitate generation of kinaesthetic perception and suggested that the sense of effort need not be the purely centrifugal mechanism first proposed by Merton (1964, 1970).

In addition to the information provided by the cutaneous and proprioceptive receptors, vision can assume a real proprioceptive function in the control of body movements and must be recognized as a powerful kinaesthetic sense (Gibson, 1966). Lishman and Lee (1973) extended this notion by opposing visual and mechanical kinesthesia and by emphasizing the quality and autonomy of the former in experiments centred on locomotion and passive transport of the body as a whole.

Through vision, kinematic movement parameters (e.g. movement velocity and/or movement end position) may provide an observer with the possibility of establishing discrimination judgments on weights lifted by an actor (Runeson and Frykholm, 1981; Bitoh, 1991).

Runeson and Frykholm (1981) showed how an external observer, watching another person handling an heavy box, was able to infer the weight of a lifted object. They concluded that visual information available in the kinetic pattern of the movement is also available as higher order properties of the optic array. Vision 'is therefore likely to have a role in what is usually taken to be the privileged domain of the haptic sense combining tactile and proprioceptive cues' (p. 733). They proposed a 'Kinematic Specification of Dynamics' principle stating that kinematic patterns specify to observers, variations in the values of dynamic factors from which they can scale their judgments of weights. The dynamic properties related to force-mass interaction were already present in the pioneer work of Johansson (1950) on the visual detection and identification of biological motion.

Bingham (1987) further extended this field of research showing that variation in the observed velocity of a lifted object, handled by a standing actor with an upward flexion of the forearm, led observers to give accurate visual judgment of weights. The observers were even able to elaborate a metric scaling of the observed weights. Velocity of the upward motion was assumed to provide implicit visual cues for judging weight to a subject observing an actor.

Cole and Sedgwick (1992) observed in a deafferented man a dramatic impairment of his ability to discriminate the weight of lifted objects when vision was precluded and concluded that most of his normal performance derived from visual cues. They also mentioned that some crude perception of force still remained with eyes shut that allows the patient to judge, by free movement of the elbow, 400 g heavier than 200 g, whereas he could discriminate 220 g from 200 g with vision.

For the past few years, we had the opportunity to carry an extensive series of experiments with a female subject, suffering a loss of large sensory fibres. She is devoid of proprioceptive and tactile sensations below the nose (Bard et al., 1995).

The present work describes investigations of the performance of this deafferented subject in a discrimination task, to approach the following questions: (i) What is the capacity of control subjects and a deafferented patient (G.L.) to discriminate weights with and without vision? (ii) If G.L. is able to use visual information, which visual cues are derived from the kinematics of the lifting movement? (iii) Does she use a specific strategy or strategies? (iv) Would external observers be able to use cues similar to those used by G.L. to establish their judgments? (v) Finally, which additional sources of information are available to G.L. to compensate for the absence of tactile and muscular proprioceptive information?

**Experiment 1**

The first experiment evaluated the capacity of control subjects and G.L. to discriminate weights with and without vision. Informed consent was obtained from all subjects participating in this study, according to the declaration of Helsinki.

**Methods**

**Subjects**

The two control subjects (one man aged 21 years, and one woman aged 23 years) and a deafferented subject (G.L.), all right-handed, participated in the experiments. G.L. suffered a permanent and specific loss of the large sensory myelinated fibres in all four limbs following two episodes of sensory polyneuropathy which affected her whole body below the nose. The illness resulted in a total loss of the senses of touch, vibration, pressure and kinesthesia in neck, trunk and limb, as well as absent tendon reflexes in the four limbs. Motor nerve conduction velocities, and needle EMG investigation of the muscles of the arm are normal. G.L. has no sensation or control of head/neck position or movement with eyes closed, showing significant drifts whenever asked to maintain or assume a definite position. G.L. is now aged 47 years and these observations have been confirmed and have proven stable for the past 17 years [see Forget and Lamarre (1987) for a more complete clinical description of G.L.]

**Equipment**

The stimuli for the discrimination task were a series of 10 weights (Lafayette), identical in appearance, of 95-195 g in
10 g steps. The 145 g weight was the reference to which each target weight was compared. Each weight consisted of a small white and cylindrical vinyl box, 55 mm high and 40 mm in diameter, closed by a lid. The boxes were filled with tiny metal bearings, varying in number according to the weight required.

Translucent liquid crystals goggles (PLATO Model S-2), the opacity of which could be changed instantaneously (< 3 ms), were used in the no-vision condition. They connected to two circular metal plates, presenting a diameter similar to that of the boxes. The metal plates were fixed to a wooden board resting on a table. They were 23 cm apart and served as supports for the judged weights. As soon as the cylindrical box was lifted, the goggles became opaque and precluded all vision.

Three Selspot cameras were used to record the x, y and z coordinates of the subject's hand trajectory while lifting the weights. An infrared light emitting diode was fixed at the dorsal aspect of the subject's index finger so that it could be tracked at least by two of the three cameras. The sampling rate was 500 Hz.

**Experimental design**

Subjects were seated on a chair facing a table supporting the board where the weights to be compared were laid. Upon a signal from the experimenter, subjects were given a maximum of 15 s to lift successively the reference (145 g), then one of the 10 target weights with the right hand. They were allowed successive up and down movements, although they could not lay the weight on the table during intermediate movements, since repositioning of the weight signalled the end of the trial. Their decision taken, subjects reported their judgment verbally: lighter or heavier than the reference weight.

Subjects were tested in two experimental conditions: with and without vision. Ten blocks of trials were given. For each block of trials, the weights were randomly presented. For each experimental condition, the psychometric function of discrimination was established, from which was extracted the point of subjective equality (PSE) and the discrimination threshold (DT) (Luce, 1959; Bonnet, 1986).

**Point of subjective equality and DT.** In psychophysics, the PSE is the point where the subject can no longer discriminate the target weight as being different from the reference weight. Therefore, it represents the weight that has become the subject's own standard, reflecting the real standard (145 g) plus or minus the subject's constant error. The DT is an uncertainty zone wherein the subject cannot discriminate between target and reference weights beyond chance. The psychometric or theoretical function adopted for linking the probability of getting a response 'heavier' to the various levels of the physical continuum was the following, considering as beyond chance the probability threshold of 0.70 (0.50 being the threshold for mere guesses):

Logistic function: \( P(\pm) \) being the probability of getting an answer 'heavier' \[
\text{Logit } P(\pm) = a V_k \ [\text{minus}] \ b
\]

where \( V_k \) = the measured variable, i.e. the weight being evaluated, \( a \) and \( b \) = the parameters of a linear function (intercept and slope) and Logit = natural logarithm.

Then \[
P(\pm) = \frac{1}{1 + \exp \left( \left[ \text{minus} \right] b \ [\text{minus}] a V_k \right)}
\]

where \( \text{PSE} = \left[ \text{minus} \right] b / a \), CE (constant error) = PSE [minus] standard (145 g), \( V_{70} = [\text{Logit } P(70)+b] / a \) and \( DT_{70} = V_{70} \ [\text{minus}] \text{PSE} \).

To study the kinematics of weight lifting, 50 additional trials in vision and no-vision for G.L. and 30 trials for each control subject were also recorded with the Selspot system. Correlations between lifted weight and kinematics measures (maximum amplitude and velocity of the first lifting movement) were calculated for each experimental condition.

In addition, accelerometry data were collected in the third experiment to determine whether specific head oscillations were associated with weight lifting. When the head was free, an accelerometer (Intertechnology Entran Sensor, Model EGCS-D Series) was fixed sagittally to a head-helmet. Head accelerations during head-free conditions were further transformed in the frequency domain using Fourier transformations.

**Results**

The PSE and DT for each subject in each experimental condition are shown in Fig. 1. The vision condition yielded a marginal difference only between G.L. (DT = 10 g) and the two controls (DT = 5.6 and 5.7 g, respectively), whereas for the no-vision condition, G.L. was largely affected (DT = 46.27 g) compared with controls (DT = 5.9 and 5.3 g, respectively). However, she was still able to discriminate the extreme weights (95 and 195 g).

These results suggest that, with vision, G.L. can correctly judge different weights in the absence of proprioceptive information. In contrast to controls, preventing the vision impaired G.L.'s discrimination capacity massively, restricting it to large differences in weight. Which kind of visual cues does G.L. use?

Peak velocity and maximum amplitude were computed for the lifting movements. The first lifting movement only showed significant correlations between kinematics and the weight being lifted. Correlations were not significant \( (r > 0.05) \) for intermediate movements (successive up and down movements during lifting) for neither experimental condition nor G.L. or control subjects. Correlations between the kinematic parameters of the first lifting movement and the weight lifted by G.L. and the controls are presented in Table 1.
Fig. 1 Point of subjective equality (PSE, indicated by vertical lines) and discrimination threshold (DT, indicated by horizontal bars) for G.L. and control subjects with and without vision.
PSE = a point that the subject assumed to be the reference weight, operationally defined as the reference weight plus the subject’s constant error. DT = the zone wherein the subject cannot give a correct answer at least 70% of the time.

Table 1 Correlations between maximum amplitude and peak velocity of the first lifting and the lifted weight for the controls and G.L., according to the visual condition

<table>
<thead>
<tr>
<th></th>
<th>Amplitude</th>
<th></th>
<th>Velocity</th>
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<tr>
<td></td>
<td>Vision</td>
<td>No-vision</td>
<td>Vision</td>
<td>No-vision</td>
</tr>
<tr>
<td>G.L.</td>
<td>-0.27</td>
<td>-0.52*</td>
<td>-0.53*</td>
<td>-0.54*</td>
</tr>
<tr>
<td>Control YT</td>
<td>-0.11</td>
<td>-0.06</td>
<td>-0.24</td>
<td>-0.14</td>
</tr>
<tr>
<td>Control GD</td>
<td>0.08</td>
<td>-0.05</td>
<td>0.14</td>
<td>-0.22</td>
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*Significant at \( P < 0.05 \).

For G.L., with vision, the correlation between peak velocity and weight is significant and negative, whereas amplitude does not correlate significantly with the lifted weights. In the no-vision condition, amplitude and velocity significantly and negatively correlate with the weights. Conversely no correlation was significant for control subjects, whether lifting movements were performed with vision or not.

The correlations suggest that, particularly in the absence of vision, G.L. attempted to produce the same force pulse to the arm for each weight. This strategy yielded a smaller movement amplitude and a smaller peak velocity when the weight was heavy and the opposite profile when the weight was light, whereas the control’s kinematic patterns show much similarity for various weights (Fig. 2).

With vision, the only parameters which had a significant correlation with the weight lifted were velocity cues, so that these appear the best candidates to explain G.L.’s discrimination. We reasoned that this should allow external observers to use the same visual cues to establish their judgements while observing the ‘G.L.-actor’. On the other hand, the observation of control subjects would lead them to poorer performances.

Experiment 2
The second experiment was therefore designed to test whether observers can benefit from G.L.’s lifting movements kinematics according to the Kinematic Specification of Dynamics principle.

The same subjects participated in Experiment 2. Three adults served as observers during the testing of the deafferented subject and the controls in the same discrimination task as in Experiment 1.

Experimental design
Three observers facing the ‘actor subjects’ were seated 1 m away to have a clear vision of the subject’s lifting hand. Each observer used a response sheet to record their estimation of the stimulus weight (heavier or lighter than the reference). The two control and the deafferented subjects performed 20 trials (10 with and 10 without vision). The percentage of Correct responses was computed for the three observers. As for the first experiment, kinematic data were recorded with the Selspot system.

Results
The percentages of correct responses obtained from the three observers are presented in Table 2. Clearly, their performance was better when they were watching G.L. than when they were watching controls. This was particularly true when G.L. was performing the task with vision. These results support the suggestion that kinaesthetic visual cues could be used to discriminate the weights lifted in the absence of proprioceptive afferent and that the deafferented subject used this strategy when generating movements.

Though no significant correlation was found between the selected kinematic parameters (peak velocity and maximum amplitude) and the weights lifted for control subjects, the observers still evaluated weights above chance when they
watched controls perform the task with vision. These results suggest that the patient attempted to use the same motor pattern on each occasion leading to specific kinematic profiles according to the target weight which allowed the observers a good estimation of the weight lifted. Controls, however, presumably using proprioceptive information for their evaluation, did not have to adopt such a stereotyped pattern. By doing so they limited the quality of the visual cues they rendered available to observers.

In the absence of vision, three cues appear to be available to G.L.: the use of a central efferent copy, a peripheral vestibular signal and a contribution from residual peripheral afferents. Since the kinematic recordings of G.L.'s lifting movements showed similar force pulses, resulting from a similar motor command whatever the weight being lifted, it is difficult to consider an efferent copy as the best candidate to explain the deafferented patient's ability to make weight judgements. Experiment 3 addresses the problem of the contribution of vestibular information and/or residual peripheral afferents to G.L.'s correct estimation of lighter and heavier weights.

**Experiment 3**

In the third experiment, four experimental conditions were established (vision and no-vision, head-free and head-fixed), and 10 blocks of trials were given, each block including the 10 randomly presented weights. In the head-fixed condition, the deafferented subject bit into a board located just in front of her to eliminate head movements and minimize vestibular information. This constraint still permitted free lifting movements, while evaluating weights in the same way as for Experiments 1 and 2.

**Results**

Figure 3 presents G.L.'s PSE and DT for the head-fixed and head-free conditions, with and without vision. With vision and in the head-fixed position, G.L.'s discrimination performance was only slightly modified compared with the head-free condition. G.L.'s DT was not modified (from 10 to 12.7 g) though her PSE shifted (from 137 to 169.5 g). Without vision, however, she showed a large modification in PSE (from 143.5 g in a head-free to 87 g in a head-fixed condition), her DT almost doubled from head-free to head-fixed (46.3 versus 74 g), so restricting her capacity for discrimination to the heaviest weight. This suggests that vestibular information plays a role in the discrimination of the lightest weight. This is in agreement with Cole and Sedgwick (1992), who found a large reduction in liminal difference for weight discrimination when they clamped the forearm of a deafferented subject and had him judge weights. Presumably forearm clamping could have reduced the contribution of the vestibular component, thus explaining their results.

The comparison of head-fixed and head-free trials, with and without vision, revealed no significant differences in the kinematic parameters of G.L., which still correlated with the weights lifted. In brief, no velocity and amplitude differences in the lifting pattern of G.L. were observed, which might explain the subject's performance. The normalized frequency spectrum of head acceleration (head-free condition), shown in Fig. 4, reveals differences for heavy and light weights. Specifically, it appears that low frequencies (~2Hz) reached a higher normalized power when heavy rather than light weights are lifted. This suggests that vestibular cues may play a role in G.L.'s weight discrimination capacity.
**Discussion**

With vision, G.L. discriminated weights almost as well as control subjects. In contrast to control subjects, the prevention of vision impaired the deafferented subject's discrimination capacity massively, though not completely. This emphasizes the importance of kinaesthetic visual cues in this subject.

Kinematic recordings of G.L.'s lifting movements revealed a significant correlation between weight and peak velocity of the first lifting movement. For control subjects, this correlation was not significant. This suggests that the subject G.L. was using a specific strategy to generate movements, which allowed her to judge the lifted weight visually. The fact that G.L. is using peak velocity also suggests that she is imposing a force pulse or a torque pulse to initiate her movement. In a previous study (Teasdale et al., 1993) we were able to establish that G.L.'s ability to generate force pulses in a reproducible way was very similar to that of controls, suggesting that in weight discrimination she does have the capacity to apply a similar force pulse for both the reference and the evaluated weight.

Surprisingly, with vision, maximum amplitude does not correlate with weight during the task. In fact, one would expect similar correlations between weight and both maximum amplitude and peak velocity. This is observed when weights are lifted without vision. This could be due to the fact that G.L. first generated a force pulse, which was further controlled visually for the last portion of the movement trajectory. A visually induced modulation of the movement thus affected the usual mechanical amplitude/velocity coupling.

When watching G.L.'s lifting performance, external observers were able to use similar cues to establish their judgments, but they failed to do so when watching control subjects. This is compatible with the control subjects and G.L. using different strategies for their weight discrimination. It supports the fact that G.L. is using kinaesthetic visual, particularly velocity cues, derived from the kinematic patterns of arm movements during the different weights presentation, whereas control subjects have proprioceptive feedback and so do not have to control their movements so reproducibly. Global kinaesthetic visual information could also be extracted, which allows an observer to discriminate, above chance, weights lifted by an actor. As proposed by Runeson and Frykholm (1981), global visuo-kinaesthetic information on dynamic properties is presumably transmitted through any biological movement. The fact that observers evaluated the visual cues issued from control subjects' performances with vision rather poorly (an average of 55% correct responses only) somewhat disagrees with the observations by Runeson and Frykholm. This discrepancy might be explained by the nature of our task, where movements (i) had no limitation in time or space other than to help discrimination, which in fact was the required response, and (ii) were restricted to movement of the arm, mainly at the shoulder, which limited the message compared with the global impression given when lifting a heavy box in Runeson and Frykholm. However, our results suggest that Runeson and Frykholm's Kinematic Specification of Dynamics principle may better apply to global lifting actions that are responses *per se* than to a pure weight discrimination paradigm.

Without vision, G.L. still had some residual discrimination capacity for target weights but her liminal difference increased hugely. The discrimination of the lightest weight disappeared after a mechanical stabilization of the head, suggesting the likely role of vestibular signals in weight discrimination when vision is absent. In a head-free condition, the power spectrum of G.L.'s head oscillations showed considerable differences in the low frequency range between heavy and light weights, which could be used by the subject to infer that a weight is different from the reference. When the head is stabilized, the differential signal, if present, is greatly reduced and does not allow the deafferented subject to judge light weights, though she still differentiates the heaviest weight from the reference. Therefore, to differentiate heavy weights the contribution of an additional source of information is required.

Kinematic recordings of G.L.'s lifting movement showed similar force pulse, whatever the weight being lifted, yielding smaller movement amplitude and smaller peak velocity when the weight was heavy and the opposite profile when the weight was light. It is suggested that similar initial impulses are poor candidates to trigger differentiated efferent copies when vision is absent. Therefore, our results may be explained without recourse to a significant contribution of an efferent copy or 'sense of effort' to weight discrimination in a subject deprived of proprioception. However, they do not rule out its contribution to such a discrimination in control subjects (Gandevia, 1982). In 1874, Wundt (Ross and Bischof, 1981) already stated that efferent signals do not generate conscious perception *per se*. Nevertheless they may be necessary to allow access to conscious experience of proprioceptive information involved in the sensation of effort, an hypothesis later revived by McCloskey et al. (1974) and, more recently, by Brodie and Ross (1984). Indeed, McCloskey and colleagues further demonstrated that, not only does the efferent signal give access to consciousness of peripheral proprioceptive information, but that 'something' about the size of the command can be sensed and graded (Gandevia et al., 1990, 1993). However, it does not seem that G.L.'s stable motor command could provide her with any significant signal for weight discrimination. To explain G.L.'s perception of heavier weights without vision and in the head clamped position, we must consider that she has some residual afferents from other somatic sources. Her neuropathy is a complete one of large myelinated sensory fibres, but she does have residual small myelinated and unmyelinated fibres including group III and group IV muscles afferents, fine sensory A-delta and C-fibres. Mense and Stanke (1983) recorded from dorsal root afferents of groups III and IV in the cat and found muscle afferents which responded to submaximal non-ischaemic fatigue. They raised the question as to whether these muscle
afferents might contribute to perception in man. Subsequently these muscle afferents have been implicated in the reflex inhibition of effer motor neuron firing, which occurs during human muscle fatigue (Bigland-Ritchie et al., 1986; Garland, 1991). It is therefore possible that these remaining peripheral afferents may contribute, as suggested by Cole and Sedgwick (1992) for their deafferented subject, to G.L.’s discrimination between heavy and reference weights.

In brief, our results demonstrate that, in G.L., pathologically devoid of reafferent sources of information on the intensity of the muscular force voluntarily produced, the role of sensation of effort, considered to be derived from efferent commands, cannot be established firmly. Conversely, the supplettive role of dynamic visual information in the perception of heaviness of lifted objects has been clearly established and shown to be surprisingly efficient.

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