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Does the type of prehension influence the kinematics of reaching?

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Kinematic studies have indicated that when a subject reaches to grasp an object, the movement consists of two primary components: (a) a transport phase whereby the hand is brought towards the object and (b) a grip phase whereby the hand changes shape in anticipation of the grasp. Using a visual perturbation paradigm, we investigated the effect of different grip component strategies upon the transport phase. The distal strategy was determined by the size of the object to be grasped: for the small object (1.5 cm o.d.) subjects naturally adopted a precision grip between the index finger and thumb; for the large object (6 cm o.d.) subjects used a whole hand prehensile grip. During 20% of the reaching trials the perturbation was introduced by unexpectedly changing the object size. The results showed that corrections to the distal program in response to the perturbation were preceded by changes in the deceleration phase of the proximal component. The data supported previous findings of two visuo-motor channels for this prehensile movement but indicated that when unanticipated shifts of only the distal program are required, both channels show modifications.

INTRODUCTION

Kinematic studies of prehension movements[9–11] have proposed that two distinct visuo-motor channels work in a co-ordinated way to program spatial positioning of the hand (transport component) and its anticipatory posturing (grip component). The visuo-motor channel for the transport component appears to process the extrinsic properties of the object, such as spatial location, to produce appropriate movement of the arm. The channel for grip codes for the intrinsic properties of the object, such as its size and shape, in order to program appropriate finger and hand shaping.

The concept of a two-channeled visuo-motor system is supported by neuroanatomical and physiological evidence. The monosynaptic component of the corticospinal tract in primates, with its role in the control of independent finger movements[14,15,20,21,23] could be recruited during the grip component. For the more proximal musculature required for the transport phase, polysynaptic ipsilateral and contralateral corticospinal and brainstem pathways would be employed[2]. For each prehension component, links between visual processing and motor pathways have been suggested from single cell recordings in area 6[7,27]. Each set of neurons codes for a motor output which is relevant to the visual input. Thus neurons which discharge during the transport component also respond to the location of an object within a focal sector of space, while neurons which are active during the performance of different types of grasps frequently respond to visual objects, provided that object size relates to the grasp coded by the neuron.

Despite the apparent independence of these two systems, some degree of interplay must exist for the performance of accurate prehensile movements. The ability of primates to perform functional grasps which range from fine precision to more gross power grips[22] implies that the relationship between the two systems adjusts according to the requirements of the task. Indeed, manipulation of the speed of the transport component has been shown to affect the grip aperture of the distal component[29,30]. Conversely, changes to the grip component can influence the transport component.

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For example, Marteniuk et al.[18] found changes in the duration of the deceleration phase of the transport component according to object size (precision grip only).

Corrections which occur following the introduction of a perturbation during the movement may further clarify the central mechanisms which coordinate the two components. Jeannerod and co-workers[4,5,24–26] examined the effects of manipulating target object position or size immediately prior to or during reach and grasp movements. In accordance with the co-ordinative structure concept[12], they found that the two components of prehension showed a loose temporal coupling as if becoming functionally linked for the execution of the task.

The current work adds to the wealth of information describing the co-ordination between the two components of this prehensile task. It used the same visual perturbation paradigm described by Paulignan et al.[26] but differed by allowing subjects to adopt a grasp which was appropriate to the object size. Subjects naturally used a precision grip for a small target object and a whole hand prehension grip for a large object. The constraint of performing a prehension task with an inappropriate distal program and the introduction of an unnatural pattern of control was thus avoided. The results showed that changes in the deceleration phase of the transport component preceded the correction of the grip component to a perturbation.

MATERIALS AND METHODS

Recording technique

Movements were recorded bidimensionally by a Selspot-System camera equipped with a 50-mm lens and placed 3 m above the horizontal working plane. The camera monitored the three-dimensional displacements of 3 active markers (infrared emitting diodes, IREDS) which were attached to the skin overlying the following areas on the dorsal surface of the right arm: (a) lateral to the lower radial corner of the index finger nail, (b) lateral to the lower ulnar corner of the thumb nail and (c) the distal styloid process of the radius. The wrist IRED (c) was used as an indication of the transport component. The digit IREDS (a and b) were used to measure the displacements of the index finger and thumb and the size of the grip aperture (index finger-thumb distance). A spatial precision of 2 mm was determined by dynamic accuracy tests. The position of the IREDS was sampled at 250 Hz and stored on an IBM 386 computer.

Subjects

Six right-handed subjects (3 males and 3 females), ranging in age from 25 to 33 years, gave their informed consent to participate; all were naive as to the purpose of the experiment.

Apparatus and procedure

Within a dimly lit room, each subject was seated comfortably and without restraint to face the working surface. The hand was placed at the starting position in the median plane. With the forearm in mid-pronation, the ulnar edge of the hand rested on a starting switch. The index finger and thumb were held opposed. The targets were two translucent dowels placed 35 cm directly in front of the hand. The tall small diameter dowel (height 10 cm, diameter 1.5 cm) was placed within a shorter large diameter dowel (height 6 cm, diameter 6 cm). These will be referred to as 'small' and 'large', respectively. Computer-controlled light emitting diodes (LEDs) embedded within the transparent material covering the working surface were used to transilluminate the dowels. One LED was placed below the small dowel, two LEDs were placed below the large dowel.

The illumination of a dowel was the signal for the subject to start the movement. The subject was requested to reach, grasp and lift the dowel accurately and rapidly. In 20 practice trials the subject was required to grasp either the small or the large dowel. Following this, all subjects adopted two clear patterns of grasp according to the diameter of the dowel. The 'small' dowel was grasped with a precision grip (PG) consisting of an opposition between the index finger and thumb[22]. The 'large' dowel was grasped with a whole hand prehension (WHP) characterized by flexion of all the fingers around the object[27]. The following describes the three types of trials: blocked, control and perturbed. For the two sets of blocked trials, each consisting of 10 movements, only the small or large dowel was illuminated (PG and WHP blocked trials, respectively). In a separate set of 100 trials, 80% were control trials whereby either the small or the large dowel was illuminated randomly. For the remaining 20% a visual perturbation was introduced by unexpectedly shifting the illumination. This was triggered by the release of the starting switch as the hand left its resting position. In 10 trials, the shift was from the small to the large dowel; as all subjects changed the grasp accordingly, these were referred to as PG-WHP perturbed trials. Similarly, the 10 trials shifting illumination from the large to the small dowel were referred to as the WHP-PG perturbed trials. In order to exclude practice effects, the sequence of trial blocks was counterbalanced across subjects.

Data processing

X and Y trajectories of each IRED and the tangential velocity of the wrist IRED were computed following filtering (Butterworth dual pass filter; cut-off frequency 8 Hz). Acceleration data were derived by differentiating the velocity data. Deceleration data were derived from the time between the velocity peak and the end of the movement. Movement time (MT) was measured as the time from the onset of the thumb IRED movement to contact of the fingers with the object (as it was seen from computation of the grip size).

For the transport component the following parameters were determined: (1) the time from movement onset to peak velocity (TPV), (2) the time from movement onset to the maximum trough of the acceleration profile, (time to peak deceleration, TPD), and (3) the time from the velocity peak (zero crossing of the acceleration curve) to the end of the movement (deceleration time, DT).

Three parameters were computed for the grip component of each trial: (1) the time from movement onset to maximum grip aperture (TGA), (2) the amplitude of the maximum grip aperture (AGA) and (3) the rate of change of the grip aperture from movement onset to maximum grip aperture (grip aperture velocity, TGV).

RESULTS

For each subject the mean values of each dependent measure were calculated for each prehension and trial type combination. The mean value for each dependent measure was entered into an analysis of variance (ANOVA) with type of grasping (PG or WHP) and type of trials (blocked, control and perturbed) as main factor. An alpha level of 0.05 was adopted for all tests of significance. Post-hoc contrasts were conducted with the Newman–Keuls testing procedure.

Blocked trials

Kinematic parameters of the transport and grasp components are shown in Table I; each value represents the mean for all subjects. In blocked trials, only the main factor 'type of grasping' was included in the analysis.

Transport component. Movement time (MT) was significantly related to the type of grasp, $F_{1,5} = 93.07$, $P < 0.0001$. The average movement time for movements using PG was 574 ms while it was 552 ms for movements using WHP.

Wrist velocity displayed a typical single peak (Fig. 1) the value of which (APV) was 1100 mm/s for the PG and 1090 mm/s for the WHP movements. On average the acceleration phase between movement onset and TPV represented 34% and 36% of MT for the PG and

TABLE I

Means (S.D.s in parentheses) of prehension kinematic parameters during blocked, control and perturbed trials

Parameters MT (movement time), TPV (time to peak velocity), TPD (time to peak deceleration), DT (deceleration time), TGA (time to maximum grip aperture), TGA2 (time of the second maximum grip aperture) and TGV (time to peak grip velocity) are expressed in milliseconds (ms). Parameter APV (amplitude of the peak velocity) is expressed in mm/s. Parameters AGA (amplitude maximum grip aperture) and AGA2 (amplitude second maximum grip aperture) are expressed in millimeters (mm).

Type of trials	*Transport component*					*Manipulation component*				
	MT	*TPV*	*APV*	*TPD*	*DT*	*TGA*	*AGA*	*TGA2*	*AGA2*	*TGV*
Blocked PG	574	200	1096	293	374	335	92	–	–	180
	(50)	(15)	(98)	(25)	(41)	(36)	(7)			(25)
Blocked WHP	552	199	1090	306	353	352	128	–	–	185
	(45)	(14)	(120)	(31)	(33)	(34)	(10)			(31)
Control PG	583	192	1164	313	387	346	92	–	–	186
	(47)	(25)	(121)	(28)	(42)	(36)	(8)			(25)
Control WHP	548	196	1180	307	356	365	127	–	–	184
	(52)	(22)	(132)	(35)	(38)	(40)	(14)			(26)
Pert PG→WHP	603	192	1180	290	413	351	91	440*	120*	192
	(62)	(23)	(121)	(35)	(45)	(30)	(11)			(30)
Pert WHP→PG	592	190	1201	269	402	355	129	–	–	187
	(49)	(21)	(144)	(28)	(41)	(36)	(13)			(29)

* Means of 5 subjects.

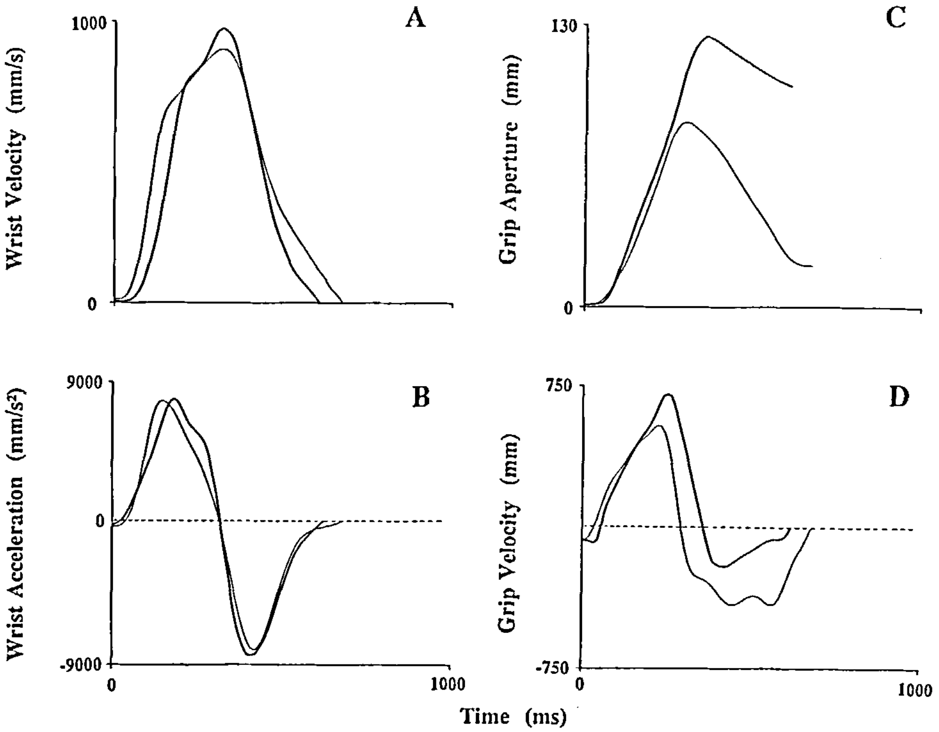

Fig. 1. Examples of the kinematic profiles for one precision grip (light line) and one whole hand prehension (darker line) blocked trial. A: velocity. B: acceleration. C: grip aperture. and D: grip velocity.

WHP movements respectively. The sharp deceleration phase (TPD) peaked at an average of 293 and 306 ms after movement onset for PG and WHP movements, respectively. Values of TPV representing acceleration time and values of DT were submitted to an ANOVA. TPV did not change significantly with the type of grasp. In contrast, DT was significantly longer for PG than for WHP (374 vs. 353 ms), $F_{1,5} = 7.84$, $P < 0.05$. In order to assess whether the different velocity profiles found in the two basic conditions belonged to the same scalar family of curves an ANOVA was conducted on the velocity profile values, which were normalized to 100 frames. Again this confirmed that DT was significantly longer for PG than for WHP, $F_{1,5} = 18.05$, $P < 0.001$, and that TPV showed no significant difference across the two conditions.

Grasp component. Grip size increased during transport of the hand to a maximum aperture before closing around the object. As expected, the amplitude of this maximum aperture (AGA) was significantly related to the grip adopted: 92 mm for PG and 128 mm for WHP, $F_{1,5} = 41.45$, $P < 0.001$.

The TGA, indicative of the temporal coordination between the grasp and the transport components, came significantly earlier for PG than for WHP, (335 vs. 352 ms; $F_{1,5} = 124.76$, $P < 0.001$) and corresponded to 58% and 63% of the MT, respectively. Thus for both types of grip, TGA occurred during the deceleration phase of the wrist as the hand approached the object.

The first derivative of grip size (TGV) was not related to the type of grip adopted: for both the PG and WHP trials it was similar (180 and 185 ms, respectively; Fig. 1).

Control trials

Transport component. For control trials, only the 'type of grasping' main factor was included in the analysis. Movement time and the temporal values of kinematic landmarks for the wrist showed no difference from those of blocked trials (Table I). For the PG trials MT was significantly longer than for the WHP trials (583 vs. 548 ms), $F_{1,5} = 30.08$, $P < 0.001$. Once again, analysis of variance conducted upon non-normalized ($F_{1,5} = 23.43$, $P < 0.001$) and normalized ($F_{1,5} = 77.56$, $P < 0.001$) data showed that DT was significantly longer for PG than for WHP.

Grasp component. The grasp component was also similar across control and blocked trials. The AGA was significantly related to the type of grasp. For PG trials AGA was 92 mm while for WHP trials it was 127 mm ($F_{1,5} = 38.38$, $P < 0.001$). TGA corresponded to 59% of MT for PG and to 66% for WHP trials and occurred significantly earlier for the former (346 and 365 ms), $F_{1,5} = 143.67$, $P < 0.001$. The TGV was the same for both PG and WHP trials (186 vs. 184 ms).

Perturbed trials

Perturbed trials which began with the illumination of one dowel were compared to those control trials that illuminated the same dowel. Thus, movement time and kinematic parameters during PG to WHP perturbed trials (PG–WHP) were compared with those during PG control trials, and parameters during WHP to PG perturbed trials (WHP–PG) to those during WHP control trials (Table I). The corresponding values for each parameter were submitted to ANOVAs where the main factor was type of trial, i.e. control vs. perturbed trials (control PG vs. perturbation PG–WHP and control WHP vs. perturbation WHP–PG).

Perturbation from PG to WHP

Transport component. The MT of PG–WHP perturbed trials was significantly longer than that of the PG control trials (603 vs. 583 ms), $F_{1,5} = 18.76$, $P < 0.01$.

The acceleration phase of the movement represented 35% of MT for PG control trials and 31% of MT for PG–WHP perturbed trials. The TPD of the wrist came significantly earlier for PG–WHP perturbed trials than for the PG control trials (290 vs. 313 ms), $F_{1,5} = 72.3$, $P < 0.001$. This important landmark represented the earliest sign of the correction needed for changing the precision grip into a whole hand prehension (Table I).

Grasp component. For five of the six subjects, the profile of the grip aperture during PG–WHP perturbed trials was marked by an inflexion: grip aperture first increased to a peak to then roughly plateau before increasing to a second peak and then closing about the dowel (Fig. 2). The first peak corresponded to the maximum grip aperture observed for the PG control trials (91 mm) and the time value of this first peak was not significantly different from that of parameter TGA in PG control trials ($P > 0.025$).

The second peak in grip size occurred later (TGA2 = 440 ms), and its amplitude (AGA2) corresponded to the size of grip observed for the WHP control trials (120 vs. 127 mm). In one subject, the first peak was missing and only a second peak was observed.

The more common double-peak pattern in grip size was clearly visible on the grip velocity profile. On this curve TGV was the same value as that found for the PG control trials (192 vs. 186). The first velocity peak was followed by a second which corresponded to the further opening of the digits (Fig. 2). The time of the lowest grip velocity between the two velocity peaks occurred, on average, at 342 ms. This represented the earliest sign of corrective digit movement for the whole hand prehension.

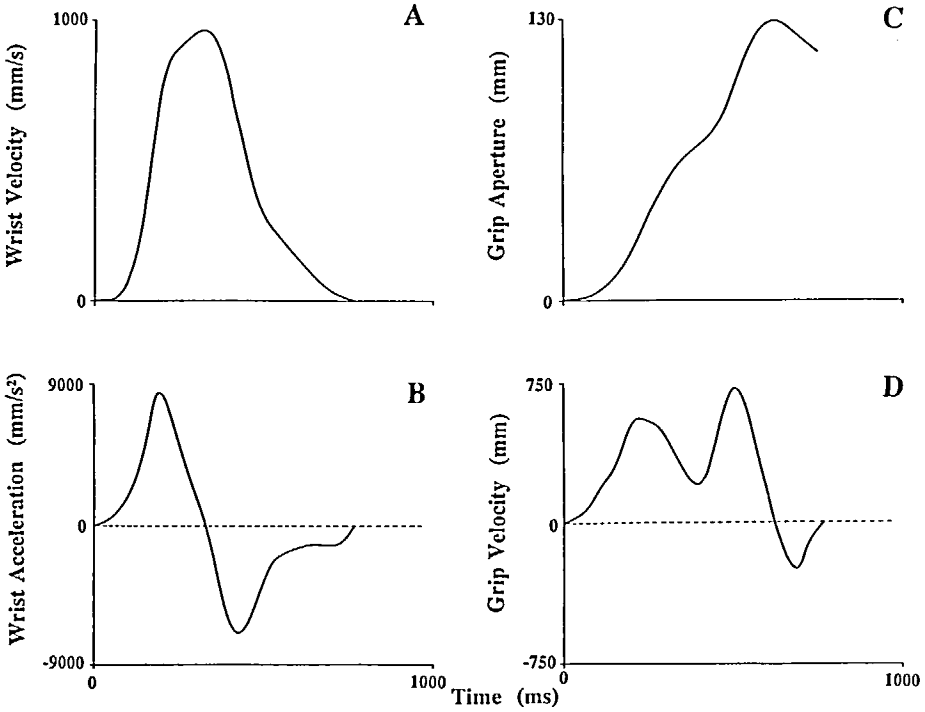

Fig. 2. Examples of the kinematic profiles for a typical trial where perturbation led to the requirement for a shift from precision grip to whole hand prehension. A: velocity. B: acceleration. C: grip aperture. and D: grip velocity. The grip aperture profile shows an inflexion as the subject adapts for the larger grip.

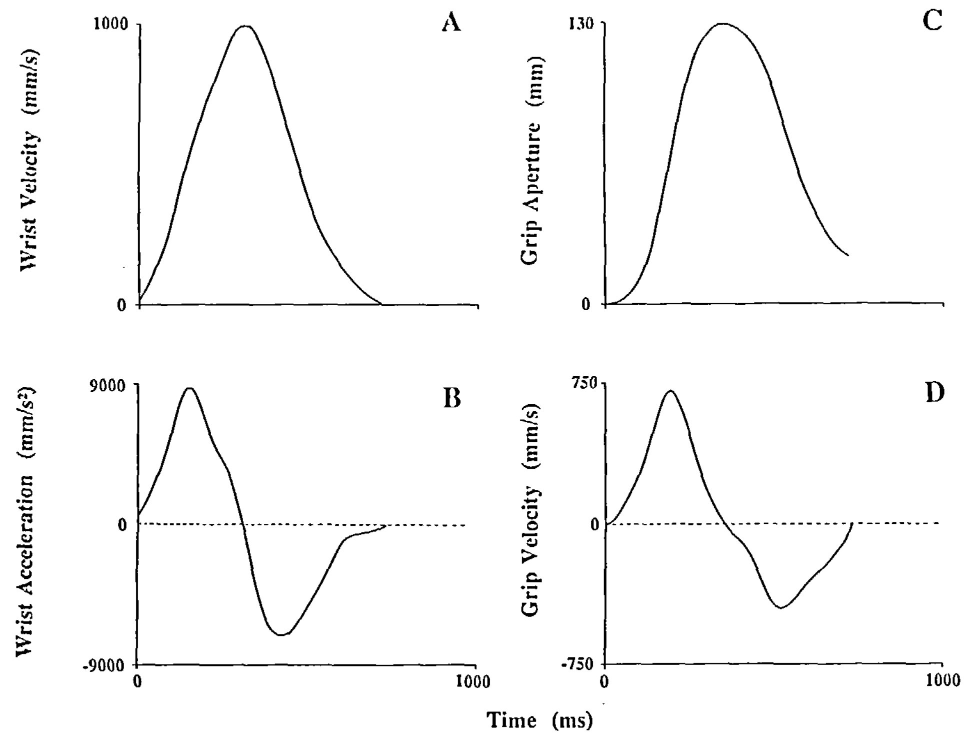

Fig. 3. Examples of the kinematic profiles for a typical trial where perturbation led to the requirement for a shift from whole hand prehension to precision grip. A: velocity. B: acceleration. C: grip aperture. and D: grip velocity.

Perturbation from WHP to PG

The MT of WHP–PG perturbed trials was significantly longer (592 vs. 548 ms) than that of WHP control trials, $F_{1,5} = 29.66$, $P < 0.001$.

Transport component. As was found for the PG–WHP perturbed trials, TPD of the wrist came significantly earlier for the WHP–PG perturbed trials, than for the WHP control trials (269 vs. 307 ms), $F_{1,5} = 58.35$, $P < 0.001$. This landmark represented the earliest sign of correction for the precision grip (Table I).

Grasp component. The grasp component in WHP–PG trials was affected by the perturbation at a late stage of the movement. In fact, parameters TGV, TGA and AGA had the same values as in WHP control trials (Table I). The profile of the grip aperture as a function of time showed only one peak (Fig. 3).

Comparison of the two perturbed conditions

An analysis of variance on parameter TPD with the type of perturbation (PG–WHP and WHP–PG) as main factor showed that TPD came significantly earlier for WHP–PG perturbed trials than for PG–WHP perturbed trials (269 vs. 290 ms), $F_{1,5} = 15.08$, $P < 0.001$. Parameters MT and TPD were also submitted to a two-way ANOVA with control trials (PG and WHP) and perturbed trials (PG–WHP and WHP–PG) as factors. This showed a significant interaction between control and perturbed trials. A post-hoc comparison showed that both MT and TPD were significantly different ($P < 0.05$) for only the WHP control trials when compared to all other trial conditions (Control PG trials, PG–WHP and WHP–PG perturbed trials). This suggested that whenever the small dowel was presented both parameters (MT and TPD) were more related to programming of the PG.

DISCUSSION

This study further assessed the interaction between the two components of a reach and grasp movement. It asked the following questions: If an unanticipated change of the distal component is required, will the proximal or transport component be affected? Additionally, if effects are observed in the latter component will these precede the changes required in the distal component?

Given the large amount of literature devoted to the reaching and grasping movement, how is this study unique? Firstly, it allowed subjects to adopt a grasp which was appropriate to object size. For a small object, subjects naturally adopted a precision grip between the index finger and thumb; for a large object, subjects naturally used a whole hand prehension. Secondly, it assessed the corrective responses to a sudden visual change in object size and in the type of grip to be adopted. Thirdly, it finds that in response to this visual perturbation of the distal component, changes in the proximal component are present AND precede those in the distal component.

In addition, this study confirms the results of previous works by assessing the relationship between the two components when no perturbation was introduced. The duration of the deceleration phase of the transport component was greater when subjects reached to grasp a small object using a precision grip than when reaching to grasp a larger object with whole hand prehension. This concurs with previous findings of a prolonged deceleration phase when reaching to grasp more fragile[17] or smaller objects[8] and points to the importance of visual feedback mechanisms during the later part of the proximal component. Similarly, when considering the characteristics of grip aperture as a function of object size, our results confirm previous well-known findings. The maximum amplitude of grip aperture covaried with object size[8]. The relative timing of this maximum aperture was earlier when a precision grip rather than a whole hand prehension was adopted. Von Hosten and Ronnqvist[28] and Gentilucci et al.[8] found this earlier change of the distal component when reaching to smaller objects. This could point to an earlier 'anticipation' of the characteristics of an object when greater precision or accuracy is required.

The originality of the initial hypothesis by Jeannerod[9] centered around the idea that during a prehension task directed to a stimulus, the recruited neural structures act independently but in parallel. Crucial to the theory of two independent channels is the concept of 'impermeability'. If processing within each channel is considered to be autonomous then it should not be influenced by programming within the other channel. The finding that characteristics of a target stimulus govern the computational requirements on both networks challenges the idea of a complete independence. Testing the relative 'impermeability' of the transport component is less simple than it may at first appear. Ideally subjects could be asked to grasp objects of invariant size by using a variety of different grips. However, this may be forcing the introduction of programs which are unnatural. Rizzolatti et al.[27], for example, have found that in monkeys, the choice of grasping type is strictly determined by object size. Additionally, each type of grasp is subserved by different neural structures[27]. If constraints are imposed upon the type of grasp to be adopted, the relative novelty of the task may dictate minimum coordination. The nervous system may find it easier to avoid complexities which would involve further interaction between the two components. Additionally, rather than synthesize new strategies, the central structures may use the mode of prehension which would naturally be adopted as a basis for the design of movements where the grasp required would not normally be chosen.

To date, changes in the first or acceleration phase of the transport component have not been observed when comparing the precision grip to whole hand prehension during preplanned and nonperturbed reaching trials[8]. On the surface, this would appear to support the concept of two stages during the transport component: a ballistic or feed-forward stage which defines both the initial state of the limb and the goal to be attained and a feedback-based stage which is employed towards the end of the movement[1]. Yet recent investigations using a visual perturbation of object location have shown that even the early part of the acceleration phase can be affected[5,24]; clearly feedback mechanisms may operate even during the early movement phases. This pointed to the importance of studying the effects of perturbations of the distal program during the performance of an alternative preplanned prehension task. This type of approach cannot easily be related to activities of daily living; it is rare to begin reaching for an object which suddenly changes. Yet, and as with all studies of the reach and grasp movement, the imposed experimental constraints provide a useful paradigm for attempting to reveal the expression of any reorganization of the control programs.

We found that the introduction of a perturbation to the distal component affected the two components in a temporal sequence: firstly the proximal and then the distal component. When compared to the results of control trials, the peak of deceleration occurred earlier as if to allow more time for the execution of a new distal program. Clearly, the implementation of one program was arrested while central networks not only prepared for that of another but also inhibited further performance of the movement which was first planned. Changes in the visual afferent input quickly resulted in the recruitment of alternative efferent pathways. Thus, when the grasp changed from a whole hand prehension to a precision grip, networks which probably use contralateral mono-synaptic pathways from the primary motor cortex need to be activated[6,13,16]. Additionally, the bilateral and polysynaptic routes from more diverse cortical regions[3,19] must be inhibited.

The time to peak deceleration was reached earlier in those perturbed trials where subjects began with the intention of performing whole hand prehension but suddenly had to adapt to a smaller object, than in those trials where the opposite conditions prevailed. Movement time, though longer than that found in control trials, was invariant when comparing these two perturbed conditions. It appeared that the expression of a constant movement duration required earlier changes when performing a task which required more individuation of the digits or a more precise strategy. Clearly, more time was allowed from the peak of deceleration to the end of movement. In fact, given the choice between a precise and a gross grip the system appeared to automatically program for the more 'difficult' task: whenever even the potential for a precision grip was presented to the subjects, effects upon movement time and time to peak deceleration were more pronounced than in situations where only a whole hand prehension was required. This may reflect the need of sending afferent input through a limited number of channels for the conscription of more localized zones within the motor cortex. Alternatively, additional time may be necessary to disfacilitate a system which might be more diverse anatomically[19].

This investigation confirms that a change of grip, rather than just a change in visual input, is crucial to the effects observed. An earlier study[26] used an identical paradigm, but subjects were requested to utilize only precision grip to grasp dowels of different sizes. In this case, no effect upon the time to peak deceleration of the transport component was observed. By unexpectedly changing the required distal strategy we found that the time to peak deceleration was affected. Clearly the necessity to change the grasp was recognized by both the transport and grasp control channels near the onset of their central planning processes.

The effects of perturbation cannot be attributed to any startle or uncertainty reactions. Firstly, the findings from the 'unanticipated' control trials correspond to those found in blocked trials, where subjects were aware of the required movement prior to its performance. Secondly, the results are reproducible and specific to a particular phase of each component rather than demonstrating more generalized effects. Thirdly, if these effects were attributable to a degree of uncertainty, they would also have been revealed in the study by Paulignan et al.[26] where a similar perturbation paradigm was applied. Similarly, this latter study serves as a control for the argument that slight differences in the vertical position of the target objects could explain the results.

In conclusion, our results show that when reorganization of a distal motor strategy is unexpectedly required during a reach and grasp movement, the nervous system quickly adapts by effecting changes in the proximal component which 'anticipate' and thus may prepare for or facilitate changes in the distal component. This does not disprove the existence of two independent visuomotor channels but shows that under conditions which stress their output, a form of coupling may be made more apparent. Programming of the proximal or transport component may be inherent in more complex channels which subserve activities of the hand and fingers in order to choose the correct type of grasp as dictated by the stimulus.

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