

RESEARCH NOTE

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Arm and mouth coordination during the eating action in humans: a kinematic analysis

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Abstract The kinematic characteristics of the eating action in humans were assessed. Ten subjects were asked to bring to the mouth pieces of cheese of different sizes (0.7 cm and 2 cm). The pattern of mouth aperture with respect to the size of the food was similar to that found for grasping differently sized objects with the hand. Mouth aperture was appropriately scaled and the time of maximum aperture was reached earlier for the smaller than for the larger piece of cheese. The deceleration phase of the arm was prolonged when the small piece of cheese had to be brought to the mouth with respect to when the large piece of cheese had to be brought to the mouth. Temporal coupling between the time of maximum peak deceleration and the maximum mouth aperture was found in seven of the ten subjects. Taken together these preliminary results suggest that coordinated actions are subserved by the use of a common coordinating schema independently from the effectors involved.

Key words Eating action · Motor control · Grasp · Motor plan · Neurophysiology · Human

Introduction

Histological and histochemical studies have demonstrated that area 6, the largest portion of the agranular frontal cortex of primates, is not uniform from a structural point of view and it can be partitioned in different subareas (Matelli et al. 1985). Of interest for the present study is the distinction between reach-related neurons in area F4 and grasp-related neurons in area F5 (for a review, see Rizzolatti 1987). For example, F4 neurons fire during arm movements to the mouth (bringing-to-the-mouth-neurons) while F5 neurons fire when the animal grasps objects with the hand or when it grasps objects with the mouth (grasping-with-the-hand-and-mouth-neurons; Rizzolatti et al. 1987, 1988).

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Given that neuronal discharge is present during grasping mouth movements in the absence of hand movements and during hand grasping movements in the absence of mouth movements, this activation seems not to depend on a particular type of synergism between hand and mouth movements. It thus appears that, independently from the anatomical effectors used to attain the stimulus, these neurons code for the aim of the motor act (Rizzolatti 1987).

The neuronal specificity for the grasping-with-the-hand movement has received independent support from neurophysiological (Rizzolatti et al. 1988) and behavioral kinematic studies (Jeannerod 1981, 1984; Gentilucci et al. 1991; Castiello 1996). In the first case, the neuron related to reaching responds to a particular spatial location of the object (3-D receptive fields) and appears to govern arm movements toward a specific space sector. The neuron related to manipulation becomes active during particular types of grasping and frequently responds to visual objects, provided that the object size is congruent with the type of grasping controlled by the neuron (Rizzolatti et al. 1988). In the second case, according to the “channel” hypothesis proposed by Jeannerod (1981, 1984), prehension movements in humans are subserved by two functionally independent channels, the “transport” component and the “manipulation” component. The transport component extracts information regarding the spatial location of the object and allows for the transformation of this information in commands that are appropriate for bringing the hand toward the object. The manipulation component extracts information regarding the size and shape of the object, thus allowing the implementation of the distal movement pattern necessary to grasp the object. Further, with regard to different types of grasp, Castiello (1996) has demonstrated that the time course of the manipulation component and its temporal relations with the transport component change according to the type of grasp. For example, the maximal hand aperture is reached earlier in the precision grip than in the clench and the whole-hand grip types.

As can be seen, while grasping-with-the-hand neurons have received both neurophysiological and behavioral

support, a grasping-with-the-mouth behavioral analysis, on the basis, for example of the size of the food or of the distance of the food from the mouth, has not yet been performed. Moreover, another point of interest is how the mouth and the arm that brings the food to it are coordinated.

The aim of the present study is to investigate the coordination between mouth aperture and the arm that brings the food toward the mouth during the eating action. In order to do so, subjects will be required to eat pieces of cheese of different size with a fork.

Rizzolatti et al. (1988; see also Rizzolatti 1987) suggests that the findings of the proximal and distal area 6 neurons are in line with the hypothesis that this area has a functional role in the sensory guidance of movements. More precisely, these authors suggest that in area 6 there is some sort of motor "vocabulary" for reaching, grasping, and holding that can be accessed by visual and somatosensory stimuli. By following this line of reasoning, it cannot be excluded that both grasping-with-the-mouth and grasping-with-the-hand neurons are subserved by a general "grasp plan," where parameterization for different components of the same motor action is similar and independent of the effector used. Thus, whether it is the mouth opening and grasping a piece of food or it is the hand opening and grasping for an object, similarities might be evident at a kinematic level. If this is the case, grasping a small piece of food with the mouth should show a different kinematic pattern to grasping a large piece of food, and this difference should resemble the one observed in different grasping-with-the-hand movements. If this is not the case, it could be proposed that, even if a different type of action system is shared by the same computational brain area, parameterization varies from action to action, or is dependent upon the effector systems involved.

Materials and methods

Subjects

Ten students (five women and five men, aged 19–25 years) volunteered to participate in this experiment. All were right-handed, reported normal or corrected-to-normal vision, and were unaware of the purpose of the experiment. Each participant attended one experimental session of approximately 1 h.

Apparatus and procedure

The experiment was conducted under conditions of normal room lighting. The participant was seated in front of the table working surface (1×1 m). Prior to each trial, the participant placed their right hand on the table. A plate was located in front of the participant with a fork placed to the right of the plate. On the plate pieces of cheese of different sizes were positioned. The cube-shaped pieces of cheese could be ~0.5 cm (small) and ~2 cm (large) in dimension.

Reflective passive markers (0.25 cm diameter) were attached to the wrist of the subject (proximal component) and on the mouth (distal component): (a) upper lip; (b) lower lip. Movements were recorded with the ELITE system. This consisted of two infrared

cameras (sampling rate 100 Hz), inclined at an angle of 30° to the vertical and placed 3 m in front of the table and 3 m apart. The calibrated working space was a parallelepiped (length 60 cm, breadth 30 cm, height 60 cm) from which the spatial error measured from stationary and moving stimuli was 0.04 mm.

A starting tone was given and the participant was required to reach for the cheese with the fork and bring it to the mouth. Subjects performed 20 trials, which corresponded to the number of pieces of cheese positioned on the plate (ten large and ten small). In order not to impose constraints, the subject was not told which cheese size they had to eat. During the experiment an assistant monitored in which trials the large or the small pieces of cheese were eaten and these trials were separately submitted to analysis. The study reported here is solely concerned with the investigation of arm-mouth coordination with respect to object size. Other manipulations, such as the effect of distance, visual feedback, laterality, speed and coordination between the reaching-to-the-food and the bringing-to-the-mouth phases are currently under investigation in our laboratory.

Data analysis

The ELIGRASP (BTS 1994) software package was used to assess the data. The data were then filtered using an FIR linear filter. The proximal component was assessed by analyzing velocity and acceleration profiles of the marker positioned on the wrist of the subject. The distal component was assessed by analyzing the distance between the two lip markers. The end of the movement was taken as the time when the lips closed on the cheese and there was no further change in the distance between the lower and upper lips. The dependent variables were: movement duration; for the proximal component, the time to peak velocity, peak acceleration, peak deceleration of the wrist marker, and the amplitudes of these peaks (the amplitude of peak velocity, the amplitude of peak acceleration, and the amplitude of peak deceleration, respectively); for the distal component, the time to maximum lip aperture, the amplitude of the maximum lip aperture, and the time from the maximum lip aperture to the time when the lips close around the fork and the food is in the mouth (closing time). In order to compare kinematic temporal data for the different cheese sizes, each temporal value was also calculated as a percentage of movement duration (relative values). Only the part of the movement of the arm from the plate to the mouth was assessed. Movement duration and kinematic variables (absolute and relative) were analyzed with an analysis of variance (ANOVA), with Size as a within-subjects factor. Regression analyses were used to determine correlations between temporal events of the distal and the proximal components. The Fisher-Z transformation of data was used for homogeneity of variance and to counteract any nonnormal distributions.

Results

Movement duration and kinematic values are reported in Table 1. In general these results suggest that the kinematic patterning of the grasping-with-the-mouth action is similar to that of the grasping with-the-hand action regarding object size. For example, the usual finding in an analysis that compares reach-to-grasp-with-the-hand movements for small-diameter objects compared with those with larger-diameter objects is a longer movement duration for the former movements, probably because they require more precision. Deceleration time is another parameter that is sensitive to object size, with longer "homing-in" phases usually observed for smaller objects. For the manipulation component, the hand reaches the maximum grip aperture earlier and is smaller for the

smaller than for the larger objects (Castiello 1996; Gentilucci et al. 1991). In the present study, it was found that the time to bring the food to the mouth was longer for the small than for the large piece of cheese ($F_{1,9} = 9.04$, $P < 0.01$; 940 ms compared with 885 ms). For the proximal component, the times to peak velocity, acceleration, and deceleration were reached at the same point in time (absolute and relative) for the small and the large piece of food. As an example, peak velocity was reached at 45% and 46% of movement duration for the small and the large piece of food, respectively. However, the amplitude of these peaks was higher for the large than for the small piece of cheese (velocity: $F_{1,9} = 23.43$, $P < 0.0001$, 1343 mm/s compared with 1224 mm/s; acceleration: $F_{1,9} = 18.32$, $P < 0.0001$, 8005 mm/s² compared with 7624 mm/s²; deceleration: $F_{1,9} = 10.21$, $P < 0.001$, 5839 mm/s² compared with 5323 mm/s²). Deceleration time, that is the time from peak velocity to the end of the movement, was longer for the small than for the large piece of cheese in absolute terms ($F_{1,9} = 21.02$, $P < 0.0001$, 512 ms compared with 470 ms). For the distal component the mouth opened more for the large than for the small piece of cheese (see Fig. 1; $F_{1,9} = 35.65$, $P < 0.0001$, 32 mm compared with 20 mm) and reached its maximum aperture earlier for the small than for the large piece of cheese in both absolute and relative terms (absolute: $F_{1,9} = 5.02$, $P < 0.05$, 521 ms compared with 543 ms; relative: $F_{1,9} = 4.78$, $P < 0.05$, 55% compared with 61%). Closing time was longer for the small than for the large piece of cheese (absolute: $F_{1,9} = 15.32$, $P < 0.0001$, 419 ms compared with 342 ms; relative: $F_{1,9} = 21.48$, $P < 0.0001$, 44% compared with 38%). Correlations between the time of peak wrist deceleration and maximum mouth aperture were found in seven of the ten subjects ranging from 0.64 to 0.94 (see Fig. 1, Table 2).

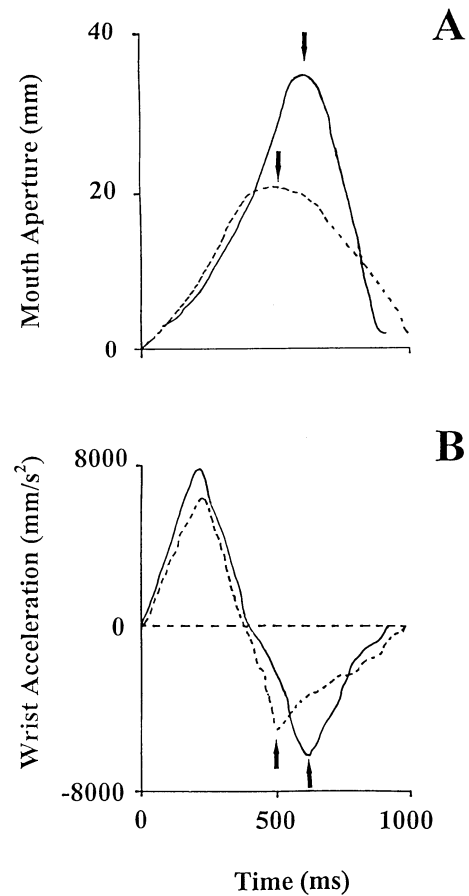


Fig. 1 **A** Examples of the mouth aperture in millimetres. **B** Examples of the wrist acceleration profile in the conditions where a large (solid line) or a small (dashed line) piece of cheese is eaten. Vertical arrows indicate the kinematic landmarks that have been considered for correlation analysis between the distal (**A**; time to max mouth aperture) and the proximal (**B**; time to peak deceleration) components

Table 1 Movement duration and kinematic values for the proximal and the distal component for the small and the large piece of cheese. SD in parentheses.

	Small Mean	SD	Large Mean	SD
Movement duration (ms)	940	112	885	83
<i>Proximal component</i>				
Time to peak velocity (mm/s)	428	53	415	34
(%)	45	4	44	4
Time to peak acceleration (ms)	238	32	222	31
(%)	25	3	25	2
Time to peak deceleration (ms)	589	86	550	69
(%)	62	5	62	6
Amplitude peak velocity (mm/s)	1224	145	1343	167
Amplitude peak acceleration (mm/s ²)	7624	777	8005	978
Amplitude peak deceleration (mm/s ²)	5323	567	5839	678
<i>Distal component</i>				
Closing time (ms)	419	56	342	47
(%)	44	4	38	4
Time to maximum mouth aperture (ms)	521	66	543	68
(%)	55	7	61	5
Amplitude maximum mouth aperture (mm)	20	2	32	3

Table 2 Correlations coefficients between time to maximum mouth aperture and time to wrist peak deceleration for individual subjects for the small and the large pieces of cheese.

Subjects	Small	Large
1	0.64	0.78
2	–	–
3	0.90	0.94
4	–	–
5	0.76	0.64
6	0.57	0.65
7	–	–
8	0.84	0.79
9	0.68	0.67
10	0.94	0.92

Discussion

The aim of the present study was to examine the kinematics of the eating action in humans. It was found that the kinematic organization that subserves this motor plan is similar to the one that characterizes the reach-to-grasp action (Jeannerod 1981, 1984). The similarity between these two coordinate actions suggests that different motor plans can share kinematic parameterization and coordination independently from the effector that is utilized.

Theories involving parallel activation encounter the problem of how different systems that are separately and simultaneously activated can be coordinated in order to achieve the goal of the action. Specific mechanisms have been advanced for ensuring temporal and spatial coordination between components of multiple-joint action (Bernstein 1967; Arbib 1981; Jeannerod 1981). Adapting Bernstein's theoretical account of a synchronizing center (ecphorator) to the present data, the existence of a double cluster of signals could be proposed, where the first signal would synchronize the fast phase of the proximal component with the aperture of the mouth, and the second signal would synchronize the decelerative phase with mouth closure. The significant correlations found between the time of maximum peak deceleration and maximum mouth aperture seem to suggest that this could be the case. Alternatively, Arbib (1981) offered the notion of a coordinated control program. Such a program is constructed of motor and perceptual schemas, where the schemas are an interaction of functional units. For example, the coordinated motor program proposed for hand movements describes a perceptual schema that can locate the object in space and then activate perceptual subschemas that recognise the object's size and orientation (Arbib 1981). This view of the schema theory might be adopted also for the present data. While the arm brings the food toward the mouth, the mouth preshapes in a way that is scaled to the size of the food.

Recently, the coordinated control program of Arbib (1981) has been revised by Hoff and Arbib (1993). In this model the mechanism proposed for temporal coordination is based on the advance information about the time needed to open and close the hand around the object as well as the time to bring the hand to the object. An important aspect of their model is that the duration of

closure time is known before the movement starts, implying that changes related to object size and other parameters, such as distance and speed, must be considered in order to estimate this time. This latter observation is confirmed in the present study, where closing time varies with respect to the size of the food to be eaten. Closing time was longer for the small than for the large piece of food even though the final closing of the mouth is similar for both sizes considering that subjects close their mouth around the fork. In addition, the fact that at some point in time we lose visual control of the food, as it comes close to the mouth, suggests the presence of a pre-planned coordinative mechanism, similar to those proposed above, so that the two components coincide in time and the arm stops at the correct time as the food enters in the mouth. Thus the mouth might be appropriately moved on the basis of proprioceptive information.

From a neurophysiological perspective, these data provide confirmation that different types of actions such as grasping-with-the-hand and grasping-with-the-mouth might be subserved by a similar neural structure. The fact that Rizzolatti and his coworkers (1988) found evidence of both grasping with the mouth and grasping with the hand neurons in area 6 suggests that some commonalities should be present between these two methods of grasping. This is confirmed in the present study, where it is shown that the two different types of distal systems, hand and mouth, have a similar "adaptation" to an object or food of a different size and are similarly correlated with their respective proximal components within a coordinated motor action. It cannot thus be excluded that both distal patterns are subserved by a general grasp plan where parameterization for different components of the same motor action is similar, independent of the effector utilized.

In conclusion, from a behavioral point of view, whether it is the mouth that opens and grasps for a piece of food or it is the hand that opens and grasps for an object, kinematics seem to be governed on the basis of similar principles. From a neurophysiological point of view, the role played by area 6 would thus be that of sending signals that command grasping and indicate how grasping is to be executed.

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