Eye, Head and Trunk Control: The Foundation for Manual Development

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INTRODUCTION

The study of early manual behavior has generally not included postural factors. When considered, however, they are found to be important for understanding the development of reaching and prehension. For example, von Hofsten (31) found that neonates who were adequately supported in a semi-reclining position, would perform aimed arm movements toward an attractive object in front of them. Grenier (10) also found more mature arm movements in neonates when their posture was supported. He concluded that it was especially important to support the head properly.

At around 4 months of age infants start to become successful in their reaching activity. Many factors influence the onset of reaching, including the ability to control gaze, balance the head, and sit with support. The development of reaching behavior is crucially dependent on postural stability. Rochat (23) reported that when infants first attain a self-sitting posture they shift toward reaching more often with one hand so that the other can be used to maintain balance. When these infants were put in an unsupported posture, they frequently fell forward if they attempted two-handed reaching. Leaning is associated with similar problems. Rochat and Goubet (24) found that only self-sitting infants would incorporate leaning to get an object if unsupported. If, however, they were supported by their hips, non-sitters would also engage in leaning forward.

It is necessary to maintain a balanced posture in order to offset gravitational forces acting on the body. If balance is to be maintained without interruption of activity, then postural disturbances need to be anticipated. In order to maintain balance during limb movements, the subject has to know about the reactive forces that arise during movement, and how reaching displaces the center of gravity of their body. Von Hofsten and Woodlaccott (36) found anticipatory adjustments in the trunk muscles during reaching by 9-month-old infants sitting astride their parent’s knee who supported them by their hips. It was the trunk extensors that were primarily preparing for the reach. The data also suggest that the abdominal muscles participate in the reach, but less as a preparation for it and more as part of bending the body forward toward the end of the reach. It is possible that these adjustments are task-dependent at this age. Van der Fits and Hadders-Algra (30) studying infants sitting in an infant chair found no evidence for such preparatory adjustments.

Postural control becomes even more important in fine manipulation, which develops toward the end of the first year of life. These fine motor skills are crucially dependent on the establishment of the direct corticomotoneuronal pathways (18). They also rely on a refinement of gaze, head, and trunk control. In the remainder of this paper, we will discuss the development of each of these skills and how they relate to the development of reaching and manipulation.

GAZE CONTROL

Stabilizing gaze on a target is most often a dynamic process. Even when the target is stationary, the subject...
may move relative to it. The gaze adjustments must anticipate the changes in direction between the eyes and the target to avoid a temporal lag. If the tracking of the target involves both head and eyes, these two component movements must be timed and scaled relative to each other. This coordination is only possible if the neural system that controls the eye movements ‘knows’ what the head is going to do ahead of time. What makes things complicated is that the head also moves for other reasons, and those movements have to be compensated by appropriate eye movements. Head movements may arise as a result of more global body movements produced during locomotion, as a result of external perturbations of the head, or from voluntary head movements. The neural circuitry controlling eye movements must predict these head movements to be able to compensate for them. In adults, eye movements simultaneously serve both compensatory and pursuit functions, making it possible to move around while fixating a moving target (6,15,17,20).

**Tracking eye movements**

There is evidence that newborn infants show some ability to track a moving target smoothly. This behavior is present, however, for large stimuli only, and then the tracking is intermittent and the gain is low (8,16,26). Bloch and Carchon (4) used a red transparent ball covering 4° of visual angle and found no smooth tracking in neonates. Aslin (1) used a black bar 2° wide and 8° high moving sinusoidally in a horizontal path. He reported only saccadic eye movements following the target up to 6 weeks of age, after which smooth pursuit started to be observed.

More recently, von Hofsten and Rosander (34,35) recorded eye and head movements in unrestrained 1- to 5-month-old infants. In the first of these studies (34), infants were shown a vertical grating with a low spatial frequency and with a centrally positioned ‘happy face’. The results revealed that this large target was smoothly pursued by 1-month-old infants with both eye and head movements. Furthermore, the tracking of the 1-month-olds was associated with a substantial lag of gaze velocity relative to target velocity which equalled 170 ms on average (see Fig. 1). This lag diminished quickly with age, however. The mean lag for the 2-month-olds was 74 ms and for the 3-month-olds 69 ms.

In the more recent study, von Hofsten and Rosander (35) studied a group of infants from 2 to 5 months of age. They were shown a smaller target (10° visual angle) moving on a white background. To investigate the development of predictive tracking, the target either moved according to a smoothly changing sinusoidal or an abruptly reversing triangular motion function. The important difference between them is that it is possible to extrapolate the sinusoidal motion, while this is not true for the abruptly changing triangular motion. It was found that 2-month-old infants tracked both kinds of motion with eye and head movements at almost unity gain. The contribution of head movements increased with age, while the contribution of eye movements decreased. Smooth pursuit was clearly present at 2 months and improved considerably by 3 months of age.

The timings of the smooth pursuits are shown in Fig. 1. At 2 and 3 months, the temporal lags of the smooth pursuit tracking for the sinusoidal target were between 60 and 70 ms. By contrast, the lags for the triangular motion were four times larger, or around 250 ms. This finding suggests that the smooth pursuit of the sinusoidal motion, but not of the triangular motion, is associated with some kind of prediction which could be characterized as local extrapolations of the target motion. By 5 months of age, the eyes were leading the sinusoidally moving target, and the lag for the triangular motion was reduced significantly. The developmental improvement is similar for the two kinds of motion, suggesting that a more cognitive form of prediction has emerged and contributes along with the more basic sensory–motor form of prediction. Anticipation of the triangular motion requires that infants predict either where or when the target is going to turn. As the target moves with constant velocity throughout each lap of motion, the motion characteristics do not reveal when or where the motion is going to reverse.

**Compensatory eye movements**

To stabilize gaze, compensatory eye movements must be initiated in response to head and body movements unrelated to the looking task. Such movements are generally of higher frequency than the smooth pursuit movements. Von Hofsten and Rosander (34) found evidence of such compensatory eye movements at 1 month of age. The remarkable finding was that these compensatory eye movements had no systematic lag. Eye and head movements were poorly scaled to each other at 1 month, but the fit improved considerably until 3 months of age. Figure 2 shows a 2-month-old girl who closed her eyes and shook her head during one of the trials. It can be seen from this figure that the gain of the compensation, which in this case must be entirely vestibularly driven, is high. The cross-correlation shows that the eyes were leading the movement of the head by 10 ms. Compensatory eye movements are intermittent and the gain is low (8,16,26). Bloch and Carchon (4) used a red transparent ball covering 4° of visual angle and found no smooth tracking in neonates. Aslin (1) used a black bar 2° wide and 8° high moving sinusoidally in a horizontal path. He reported only saccadic eye movements following the target up to 6 weeks of age, after which smooth pursuit started to be observed.

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movements in response to head movements have traditionally been conceived in terms of the vestibular–ocular reflex (VOR). Reflexes generally show some lag, however, which is not true for the eye movements shown in Fig. 2. It should be noted that the head movements in Fig. 2 are self-produced and predictable. They are part of an ongoing action.

In summary, the results of von Hofsten and Rosander (34) show that the compensatory eye movements were coordinated with the tracking eye movements. In other words, young infants seem to simultaneously be able to track a visual target and to compensate for head movements unrelated to the tracking. These two abilities develop in parallel.

DEVELOPMENT OF HEAD CONTROL

Little is known about the early development of head control and the role of head movements in infant visual tracking. The reason is that, in most studies, infants have been restrained from moving their head. However, from the studies permitting free head movements, it is evident that from birth the head actively helps to direct gaze.

Neonates have some control of their head, and Prechtl (22) reported that they are able to balance their head for a few seconds in a sitting position. Their head movements also contribute somewhat to visual tracking. However, Bloch and Carchon (4) found that neonates tended to track a moving target with eye movements as far into the periphery as possible before turning the head.

The contribution of head movements to visual tracking increases rapidly over the first few months of life. Bloch and Carchon (4) found that 1-month-olds used the head significantly more than newborns in tracking. In the two studies by von Hofsten and Rosander (34,35), head movements contributed to tracking at all ages studied, even at 1 month of age. However, as infants cannot balance their head for an extended period of time at that age, they require passive support to engage the head in tracking an object. Once infants are able to balance their heads, at around 3 months of age (9,19,28), they spontaneously raise it from the support, and tracking then becomes more flexible and efficient. Von Hofsten and Rosander (35) found that, in some infants, head tracking even dominated by 5 months. This is in line with Daniel and Lee (7) who studied tracking in 11- to 28-week-old infants and found that some of their oldest infants used head movements almost exclusively to track moving targets. Von Hofsten et al. (37) reported that head movements could account for all the tracking of 6-month-old infants presented with an object moving diagonally over a large screen.

DEVELOPMENT OF TRUNK CONTROL

The development of independent sitting represents one of the premier accomplishments during the first year of life. It is not until 6 to 7 months of age that infants are capable of sitting without support (2). This behavior represents a formidable challenge to infants, because the support surface has been reduced significantly relative to the surface available to infants who are lying supine. When sitting without support, it is necessary for infants to ensure that their center of mass is balanced within the stability limits established by biomechanical constraints. Brisk adjustments in hip and trunk muscles are necessary to resist sudden disturbances to postural equilibrium.

The achievement of this new motor skill requires not only the development of the motor response synergies necessary for independent sitting, but also the coupling of perceptual information to modulate these synergies. Hartbourne et al. (11) reported that infants between 2 to 3 months of age, who were first supported around the trunk and then released, showed considerable variation in the muscle activation patterns of the back and hip necessary for independent sitting. By 4 to 5 months of age, these infants restricted their activation to direction-specific muscle responses. In spite of this restriction, the evidence suggests that the muscle synergies are still quite variable (12,13). Hirschfeld and Forssberg (13) suggested that the muscles necessary for sitting do not show a consistent activation pattern until the infant gains some experience with sitting. It was hypothesized that these response synergies demanded perceptual modulation that became available only with experience.
Some evidence supporting this conjecture is available from a recent longitudinal study testing sitting infants’ compensatory responses to perceived self-motions induced by a moving room (25). In this study, infants were tested once every 4 weeks from 4 to 9 months of age. Their postural responses were assessed while they sat in an infant seat mounted with load cells for measuring their changing center of pressure. Infants were visually stimulated by oscillating the walls and ceiling of the room toward and away from the direction they were facing. Postural responses were measured in three conditions: walls oscillating at a constant frequency (0.6 Hz), walls oscillating at a variable frequency (ranging between 0.1 and 0.9 Hz), and walls remaining stationary (i.e. no movement).

Previous research had suggested that infants begin to scale the force and timing of their postural compensations as early as 5 months of age, but this coupling is very modest until 7 and 9 months of age when the covariation between postural sway and wall movements shows a profound improvement (3). Although this developmental improvement might reflect many different factors, the correspondence between the onset of independent sitting and the improvement in visual control suggested that this association was a reasonable candidate for explaining the developmental progression.

The data from Rose and Bertenthal (25) offered a first step toward addressing the contribution of sitting experience to postural control more directly. In this study, the data were analyzed relative to the onset of independent sitting, and infants’ responses from the period 2 months prior to 2 months following the onset of sitting were compared. The principal analysis involved cross-correlations between postural sway and room movements in order to assess whether the covariation between these two variables improved with sitting experience. For each trial, we calculated the highest cross-correlation and its temporal lag. Figure 3 (top panel) shows how the cross-correlations increase most rapidly during the period straddling the onset of sitting. This result is true for both the constant and variable frequency conditions, suggesting that the coupling is assembled in real-time and does not benefit very much from the greater predictability associated with the constant frequency condition. Figure 3 (bottom panel) shows how the time lags for these peak correlations decreases as a function of sitting experience. Apparently, the temporal coupling between the visual information and the postural response increases significantly with experience. This improvement reflects increasing anticipation of postural changes as well as more rapid responses to the perceived perturbations. In sum, these results are consistent with the previous suggestion that there is an influence of vision on trunk control that develops in conjunction with sitting experience.

DEVELOPMENTAL CHANGES IN REACHING

As previously discussed, reaching depends on the coordination of the head and eyes and hands (5,29). These actions require a nested hierarchy of stabilized systems in which the eyes and head are supported by the trunk in either a sitting or standing posture. Van der Fits and Hadders-Algra (30) found that already at 4 months, when successful reaching emerges, reaching movements are accompanied by complex postural adjustments. The requirement for stable trunk support is exceptionally challenging, because the trunk often participates in the act of reaching (14). Consider, for example, how a person will sometimes lean forward or twist to the side to reach for an object. In these tasks it is necessary for the trunk and arm to move in coordinated fashion. Even infants show this coordination following the onset of independent sitting (24).

The development of successful reaching thus involves learning to satisfy the dual demands of the trunk maintaining a stable frame of reference while it also participates in bringing the hand to the target. During the first few weeks of reaching, this coordination is not present. Recall that infants begin reaching successfully for objects by 4 months of age, but they are not capable of balancing their trunks and sitting independently until around 6 to 7 months of age (2). If stable trunk support is indeed important in the development of reaching, then it should be possible to show that significant changes in reaching are associated with improvements in trunk control. Interestingly, a number of
longitudinal studies on the development of reaching report
significant changes in the structure of reaching around 6 to
7 months of age (27,33). Similar changes were also
observed in the previously described longitudinal study test-
ing infants’ postural control (25). In addition to testing visual
control of sitting, this study tested the same infants for their
skill in reaching for small toys that translated horizontally in
an arc around them. The toys were presented at three speeds
(7.5, 15, 30 cm/s), and infants showed continuous improve-
ments in contacting these moving toys until 28 weeks of age
(see Fig. 4, top panel).

It is important to appreciate why this task necessitated
predictive control of reaching. The toy was moving continu-
ously; thus, reaching could not be guided by the current
location of the toy but rather by where it would be located
at the time that the hand contacted the toy. Remarkably,
infants showed some predictive reaching from 4 months of
age, as evidenced by their contacting the toy directly. Addi-
tional evidence of anticipatory responding was associated
with the hand selected for reaching. Initially, infants reached
predominantly with both hands together (see Fig. 4, bottom
panel). As infants began to anticipate better the trajectory
of the target, they increased their likelihood of reaching with
the hand that was contralateral to the side on which the toy
appeared. By choosing the contralateral hand, infants allowed
themselves more time to reach for the moving target. It has
been found that the faster the target, the stronger is this
tendency (32). Eventually, this strategy became less impor-
tant because infants developed better control of their trunks,
and were able more quickly to pivot their head and trunk
toward the direction in which they expected the toy to
appear. This improved trunk control allowed infants to
reach more frequently with the closer, ipsilateral hand.

In order to avoid any misunderstanding, we want to
emphasize that the development of reaching is a function
of many different factors, including distance perception,
learning to scale neuromuscular forces, coordinating differ-
ent limb segments with other biomechanical factors, such
as gravity and intersegmental dynamics, mapping visual
and proprioceptive information to the response synergies,
selecting which hand will contact the target object, etc.
Nevertheless, the development and maintenance of a stable
base of support from which to engage in reaching is founda-
tional to all these other factors. It is for this reason that we
have chosen to emphasize how eye, head, and trunk control
are related to each other and to the development of reaching.
Once a stable frame of reference is available to the infant,
it is possible for infants to achieve greater flexibility and
accuracy while reaching.

CONCLUDING COMMENTS

In this brief review, we have highlighted how reaching
involves much more than the coordination between vision
and reaching. Successful reaching involves a nested hier-
archy of eyes, head, and trunk organized in such a way that
the hand is guided toward the target object. The location
of the object is initially given in retinal coordinates, but this
information must also be transformed into head and
shoulder coordinates to insure the coordinated participation
of the different body segments (21). Moreover, the relation
between the different body segments and the object is
continuously changing during a reach. For this reason,
reaching for distal objects is necessarily a dynamic process
demanding mutual and reciprocal processing of the relevant
perceptions and actions. It is quite remarkable that infants
develop the capacity for successful reaching at such a young
age when considered from the perspective of such a com-
plex system of interacting behaviors.

REFERENCES

31.
5. Bullinger, A. Cognitive elaboration of sensorimotor behavior. In:


25. Rose, J. L., BERTENTHAL AND VON HOFSTEN


