These experiments tested the hypothesis that the ability to change sensorimotor set quickly for automatic responses depends on the time interval between successive surface perturbations. Sensorimotor set refers to the influence of prior experience or context on the state of the sensorimotor system. Sensorimotor set for postural responses was influenced by first giving subjects a block of identical backward translations of the support surface, causing forward sway and automatic gastrocnemius responses. The ability to change set quickly was inferred by measuring the suppression of the stretched antagonist gastrocnemius responses to toes-up rotations causing backward sway, following the translations. Responses were examined under short (10–14 s) and long (19–24 s) inter-trial intervals in young healthy subjects. The results showed that subjects in the long-interval group changed set immediately by suppressing gastrocnemius to 51% of translation responses within the first rotation and continued to suppress them over succeeding rotations. In contrast, subjects in the short-interval group did not change set immediately, but required two or more rotations to suppress gastrocnemius responses. By the last rotation, the short-interval group suppressed gastrocnemius responses to 33%, similar to the long-interval group of 29%. Associated surface plantarflexor torque resulting from these responses showed similar results. When rotation and translation perturbations alternated, however, the short-interval group was not able to suppress gastrocnemius responses to rotations as much as the long-interval group, although they did suppress more than in the first rotation trial after a series of translations. Set for automatic responses appears to linger, from one trial to the next. Specifically, sensorimotor set is more difficult to change when surface perturbations are given in close succession, making it appear as if set has become progressively stronger. A strong set does not mean that responses become larger over consecutive trials. Rather, it is inferred by the extent of difficulty in changing a response when it is appropriate to do so. These results suggest that the ability to change sensorimotor set quickly is sensitive to whether the change is required after a long or a short series of a prior different response, which in turn depends on the time interval between successive trials. Different rate of gastrocnemius suppression to toes-up rotation of the support surface have been reported in previous studies. This may be partially explained by different inter-trial time intervals demonstrated in this study.

Key words Automatic responses · Balance · Balance control · Central set · Set · Sensorimotor set · Posture · Postural control

Introduction

Ankle-muscle responses activated by the movement of a support surface in standing subjects are initiated between 50–70 ms for monosynaptic responses. This response is followed by polysynaptic activity occurring between 70–120 ms for the stretched plantarflexors responses to backward translations causing forward sway. In toes-up rotation causing backward sway, the stretched plantarflexors respond at the same latency as in backward translation, while the shortened tibialis anterior are activated at 140–160 ms.

These polysynaptic responses are considered automatic, because they are not easy to modify by volition (Diener et al. 1991). The amplitude of the responses, however, depends on the subject’s set. If subjects are given the same perturbation repeatedly, they show a tendency to respond based on prior experience rather than on the
actual current surface perturbation characteristics. For example, subjects initially over-respond to a new small amplitude perturbation after responding to a prior series of larger perturbations. Similarly, after a prior series of small amplitude perturbations, subjects under-respond to a new larger perturbation (Horak et al. 1989).

Set is the nervous system’s tendency to behave or to respond in a particular way due to prior experience or context (Chong 1997; cf. Buchwald et al. 1975; cf. Prochazka, 1989). In balance control, when a condition or its context changes, set must change accordingly. A different pattern of response must be activated. To successfully change sensorimotor set, the transmission of sensorimotor pathways must be changed, by appropriately activating and suppressing specific muscle activities. One way to infer the ability to change set quickly for balance control, is to measure muscle responses when perturbation conditions are changed. Muscles needed to maintain balance must be activated. Others that are irrelevant or could worsen balance must be suppressed. For example, when a person stands on a moveable platform, and the platform moves backward causing a forward sway, the stretched gastrocnemius muscle shows a large response to return the body to its original position. On the other hand, when a person is subjected to a platform toes-up rotation causing a backward sway, the stretched gastrocnemius muscle, if it shows a large response, would destabilize balance more than that caused by the platform movement. Therefore, the person must change his/her set by reducing or suppressing the gastrocnemius response.

Thus, although afferent signals from the ankles during translations and rotations may be similar, the nervous system can change from one response to another, using current incoming sensory information from other body parts, such as the knee, hip, and head (Allum and Honegger 1992; Nardone et al. 1990). Reliance on current sensory information to change set may be difficult if sensorimotor pathways, which have been primed to respond to one condition from prior experience, now predispose subjects to respond the same way in the next trial. Subjects do not quickly suppress the stretched antagonist gastrocnemius response to toes-up rotation after responding to a long series of backward translations requiring a large response to maintain balance. Instead, a large response occurs in the first rotation, followed by gradual reductions in successive rotations (Nashner 1976).

Although this provides strong evidence for the influence of prior experience on the changeability to set, other studies reported variable amounts of gastrocnemius suppression in response to toes-up rotation following backward translations. For example, when a long inter-trial interval of 30–40 s was used, subjects showed an immediate suppression of gastrocnemius response to the first rotation following a long series of backward translations (Hansen et al. 1988). Although the inter-trial interval was not reported in the original study (Nashner 1976), it is possible that the subjects’ set may be influenced not only by prior experience, but may also depend on the intervals between successive trials. That is, sensorimotor set may be more difficult to change, not only due to a long series of identical perturbations, but also if the perturbations are presented in rapid succession. The issue of inter-trial interval has never been considered in previous surface-perturbation studies. The purpose of this study was to test the hypothesis that the ability to change sensorimotor set quickly for changes in perturbation stimuli depends on the inter-trial time interval between successive perturbations.

Materials and methods

Thirteen adults, five males and eight females, between 20 and 30 years old participated in the study, which was approved by the Institutional Review Board. All subjects were healthy and free from any neurological or musculoskeletal disorders. Subjects were randomly divided into a short- and a long-interval group. The short-interval group had six subjects (three males, three females), mean age: 24±2 (s.d.) years, mean height: 169±9 cm, and mean foot length: 23±1 cm. The long-interval group consisted of seven subjects (two males, five females), 24±4 years old, mean height: 174±16 cm, and mean foot length: 23±2 cm. Subjects had no prior experience with platform-perturbation experiments. During the experiments, subjects stood with their arms lightly crossed at the waist and looked at a poster placed at eye level 2 m in front of them. The instruction was to maintain in-place balance during the perturbations and to stand still between trials.

Experiment 1: backward translations followed by toes-up rotations

Experiment 1 tested the hypothesis that inter-trial time interval affects the ability to change sensorimotor set after a long series of identical perturbations. Subjects were first given seven backward translations of the support surface: 6 cm at 15 cm/s. Translations were immediately followed by seven toes-up rotations: 4° at 20°/s. The two conditions gave very similar degrees of ankle dorsiflexion in the first 70 ms of perturbation onset, before automatic responses were initiated: 22°/s in backward translations and 20°/s in toes up rotations.

Each trial was triggered after subjects returned to their initial position (±5 mm) and remained quiet, monitored by the experimenter using center of foot pressure displayed on an oscilloscope. Center pressure was derived from vertical forces measured by four strain gauges buried within the moveable platform. Data collection, starting 300 ms before platform perturbation, lasted 3 s. In the next 4–6 s, the platform was returned slowly to its original position at 3 cm/s in backward translations and 2°/s in toes-up rotations. Subjects remained on the platform during the return. In sum, the time window from platform perturbation to its return was 7–9 s.

The short-interval group had a pause of 3–5 s between the end of platform return and the onset of the next perturbation. The long-interval group was given pauses between 12–15 s. Pause times varied slightly from trial to trial because subjects had to be centered and remain quiet before each perturbation was triggered. The total time interval between trials was 10–14 s for the short-interval group and 19–24 s for the long-interval group. The median inter-trial time difference between the two groups was 9.5 s.

Experiment 2: alternating between backward translation and toes-up rotation

To test the hypothesis that the ability to quickly change sensorimotor set is easier when there is no prior experience of a long series of a different perturbation, an additional experiment was conducted. Instead of giving subjects a long series of translations and then rotations, translations and rotations were given alternately over 14 trials, starting with translation. This required subjects to