THE CONTRIBUTION OF INERTIAL AND SUBSTRATAL INFORMATION TO THE PERCEPTION OF LINEAR DISPLACEMENT.

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Humans are able to walk to an imagined goal in the absence of external cues, as documented by an extended literature (for overview see Elliot, 1990). Despite efforts to experimentally manipulate the motor part of the system (Elliot, 1987; Corlett et al., 1990) it has not become clear from which source the necessary information about the distance walked is obtained.

This study investigates the processing of distance walked by first combining and then experimentally separating the inertial and the substratal components of the underlying system.

The subjects (Ss) try to reproduce a previously seen distance when blindfolded and earphoned with white noise by walking or being driven towards the imagined goal. Three experimental paradigms are used: (A) Walking in a hallway, (B) Walking on a motordriven conveyor–belt or (C) Indicating the goal during passive transport in a trolley (C). In (A) intertial and substratal information are available to the Ss, whereas in (B) only substratal and in (C) only intertial information is available.

A. Walking in a hallway (intertial and substratal information).

Al: Walking with self–adopted step length.

In a long hallway the distance of 10 m from the starting point is marked by a cardboard square fastened 2m above ground. After inspection of the marker the S is blindfolded and asked to walk to, and stop below, the imagined goal. The S is asked to walk with five different velocities (from „very slow" to „very fast") chosen according to her/his personal standard. The distance indicated, the walking–time and the number of steps are measured. From these data mean velocity, mean step length and mean step rate could be gained.

Result

16 Ss out of 21 Ss indicate a larger distance than veridical if the velocity is slower than „normal" and a smaller one at greater velocity (Fig 1a and Fig 2a, fat curve). There is a fixed relationship of velocity (v) to step length (ls), hence to step rate (fs) (as previously found by Grieve and Gear, 1966). Consequently the distance walked is also correlated with ls and fs (Fig 1b, c and Fig 2b, c).

A2. Walking with prescribed step length.

The correlation between velocity and step length found in experiment Al is uncoupled by varying step length (small ls, medium ls and large ls) in all 5 velocity classes.

RESULT: In one group of Ss now the perceived distance information is no longer correlated to velocity, but clearly to step length (S1, Fig 1b). In the other group, perceived distance is strongly correlated to step rate (S2, Fig 2c). Out of 15 Ss 9 are of type S1 and 6 of type S2.

B. Walking on a motor–driven conveyer–belt (substratal information only).

Although the Ss know that they walk on a conveyor–belt and hence remain objectively fixed in space, most Ss (11 of 16) are readily able to imagine that they move forward then and to iniciate when they appear to have reached the goal. These Ss show the same idiosyncratic dependency on ls or fs as in walking along the hallway in Exp. A2.

C. Passive transport (intertial information only).

The Ss stand on a low trolley, which is either moved smoothly or rhythmically to imitate steps. The Ss are asked to signal when they feel to pass the goal.

RESULT: All 21 Ss undershoot the mark at slow and overshoot it at fast velocities, that is, the formal relation between velocity and distance estimation shown in Exp. Al reverses polarity (Mittelstaedt and Glasauer, 1991).

There is no significant influence of the mode of movement, head position or head–movements during passive transport.

The relevance of the results on distance processing for navigation is checked in a homing task featuring a triangular excursion, with varied conditions along the second leg (fast – slow, active – passive), Now the angular homing errors behave as tough the linear integration variable would indeed be subject to the same errors as those found above (Mittelstaedt and Glasauer, 1991).

Conclusions and hypotheses

The results of the hallaway–experiments are reproducible on a conveyor–belt, where only substratal information is available. Therefore it is concluded that substratal information (e.g. from proprioceptors or efference copies) is sufficient. Hence inertial information obtained from linear accelerometers (e.g. from the otolith system) is not necessary for the estimation of distance walked.

On the other hand the experiments with passive transport (Exp. C)' show that distance can be estimated even in the absence of substratal information. The errors are velocity–(acceleration–) dependent, and minimal at a velocity corresponding to normal walking speed. The information could be gained by a) temporal integration over a measurement of the initial acceleration, or b) from a comparison of elapsed time with learned relations between time and distance walked at standard velocity. In the case of b) Ss should undershoot the goal at lower and overshoot it at faster velocities. This is indeed the case but, at a given distance of the goal, time between start and stop is not constant as should be expected according to hypothesis b). In the case of hypothesis a), however, double integration of the otolith output derived from the standard assumptions about otolith dynamics is insufficient to explain the results of Exp. C.

We suggest the following hypothesis: A leaky integrator (time constant τ) is initially loaded by the reference value D. While the S is walking, a measurement of walking speed is integrated over time and the result subtracted from the original load. The gain factor K of the unloading is adjusted so that, by the combined unloading effect of the velocity–integration and the leakage, the load will become zero at the right distance, provided the S's velocity is standard. Thus the velocity dependence of distance d estimated by the Ss is given by the following equation:

$$d = \tau v \ln \left(1 + \frac{D}{K \tau v}\right)$$

If in forward walking the normally fixed relationship between velocity and step length or step rate is uncoupled, the perceived distance for one group of Ss is no longer correlated to velocity but clearly to step length (in S1, Fig 1b). For the other group, correlation to velocity is decreased but still obvious whereas the close relationship to step rate is maintained. This leads to a different hypothesis how Ss gain information about position:

For ls – dependent Ss (type 1) a spatial integration procedure is suggested by summing up the subjective step length ls^* of each step:

$$d = \sum_{1}^{n} ls^*$$

For fs–dependent Ss (type S2) the maintained relationship to velocity suggests a temporal integration procedure. There are two possible solutions:

1. A temporal integration of the subjective velocity v^* derived from the subjective step rate fs^*.

$$d = \int_{0}^{T} v^* (fs^*)\, dt$$

2. A temporal integration of the subjective step rate fs^* multiplied by a normative factor l_N (possibly representing a standard step length)

$$d = l_N \int_{0}^{T} fs^*\, dt$$

Errors in walking with self–adopted step length should therefore be due to a wrong estimation of the subjective parameters ls^* or fs^* versus the objective ones. The causality of the idiosyncratic difference between the two groups is unknown.

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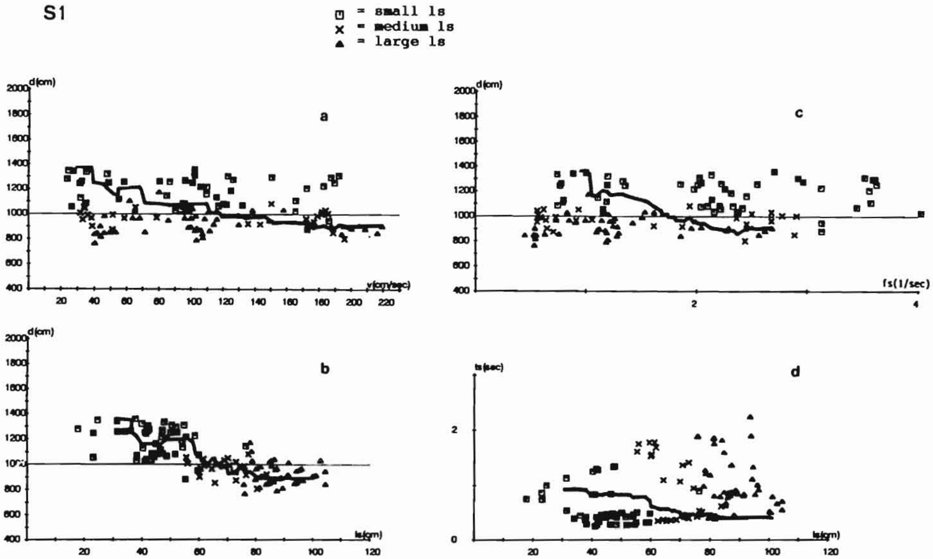

Fig 1 Data of experiment A2 from a single subject of type S1 at 3 prescribed step lengths (ls): a, b, c: estimated distance (d; objective distance = 1000 cm) as a function of velocity (v); step length (ls) and step rate (fs); d: step duration (ts) as a function of step length (ls). The fat continous curve shows the smoothed means of the respective data from the same S in Exp. A1. Note that the latter fit the A2 data only in diagram b. This indicates that distance estimates are based in step length (ls) in this S of type S1.

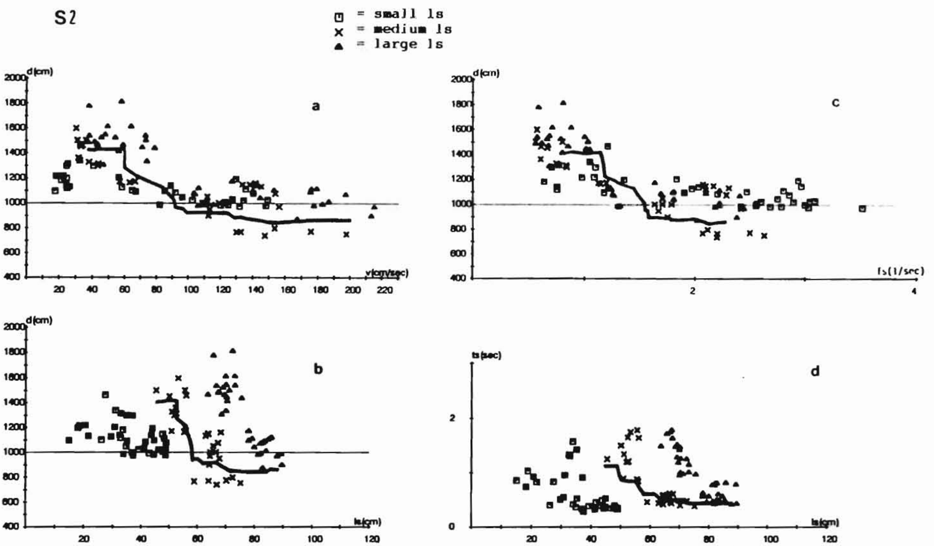

Fig 2 Same data and arrangements as in Fig 1 from a S of type S2. Here, only diagram c shows a good fit between data from Exp. A1 and A2, pointing to step rate as the basis of distance estimation in this S of type S2.