COMPARISONS OF INDICES OF MOVEMENT DISCRIMINATION: PSYCHOMETRIC FUNCTION, INFORMATION THEORY, AND SIGNAL DETECTION ANALYSIS

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Abstract

Quantitative assessments of movement discrimination ability are used in sport and rehabilitation to gain insights into the mechanisms of neural function, skill performance under different conditions and recovery after injury. Here, we have for the first time compared three psychophysical measures of discrimination of extent of ankle movements. The movement discrimination sensitivity indices were; the just noticeable difference (JND) derived from the psychometric function, the amount of transmitted information (TI) from information theory, and the area under the ROC curve (AUC) from non-parametric signal detection analysis. Absolute judgements were obtained from 25 participants for the extents of active ankle inversion movements made to physical stops at different depths. Only the AUC showed a significant difference in discrimination scores with depth and a downwards linear trend of lesser scores with greater movement extents. These results are consistent with the previous findings of Cattell and Fullerton (1892) and Magill and Parks (1983).

Movement sensitivity, or proprioception, measures are among the first methods used in the psychophysics domain in the late 19th century. Fechner used lifting different weights to gain insight into the relationship between measurable difference in weights and related perception (Fechner, 1966). Continuing in his footsteps, most of the psychophysicists during this early period examined the movement sensitivity question with proprioception tests (Cattell & Fullerton, 1892; Fernberger, 1913; Peirce & Jastrow, 1885; Urban, 1910). However, unanswered questions related to movement sensitivity did not stimulate research for the next 100 years; the topic is mostly only introduced in relation to the early history of psychophysics.

During this period, however, other areas such as neurophysiology, rehabilitation medicine and physiotherapy have utilised proprioceptive sensitivity measures to assess interventions intended to improve motor function, or to describe the mechanisms underlying proprioception and motor control. Most of the methods employed in these fields have used passively applied movements to find a threshold for detection (Refushauge, Kilbreath, & Raymond, 2000) or have used open-ended movements such as reproducing a criterion movement on one limb with a contralateral limb (Willems et al., 2005). Accuracy in matching end position, however, may not reflect the precision of discriminating the differences in position (John, Goodwin, & Darian-Smith, 1989), and there are only a handful of studies in this area utilising the methods of constant stimuli and psychophysical measures. In fact Cattell's statement (1892) that the method of constant stimuli was the most reliable psychophysical measure for assessing movement discrimination was unknown in the domains of allied health science until 1990s.

Recently, some researchers have used the method of constant stimuli to obtain the just noticeable difference (JND) measure to quantify the sensitivity of the arm movement extent, beginning with Carlton & Newell (1985), and Magill & Parks (1983). Meanwhile with the advent of information theory by Shannon in the 1950s (Shannon & Weaver, 1963), some neurophysiologists have employed an information index to quantify proprioception sensitivity, namely transmitted information (TI). For example, Clark and colleagues (1995) used the amount of TI to resolve the maximal range of motion that can be discriminated at the finger. As this measurement method is based on the confusion matrix, the use of constant stimuli can also be applied to obtain the TI value. Waddington, Adams and colleagues have used the method of single stimuli with absolute judgement to create a receiver operating characteristic (ROC) curve and the area under the curve (AUC) for a kinaesthetic sensitivity measure. In particular, this group of researchers have examined sensitivity at a variety of joints (e.g., neck, ankle, leg, and shoulder) with different test conditions to examine effects of joint pain and joint injury (Lee, Nicholson, Adams, & Bae, 2005; Waddington & Adams, 1999).

To date, no studies have compared different sensitivity measures in order to examine the robustness of each method in comparison with the method of constant stimuli. We believe this to be a necessary methodological comparison that is relevant to future research requiring accurate and practical evaluation of proprioception. To answer the question, the task we chose was judgment of extent of ankle inversion movement at three different base depths, performed in an upright posture. Ankle inversion movement was actively produced by the subject to a defined angle. With a variation in the angle of the stimulus presented, and absolute judgement recorded for each trial, it was possible to compare different sensitivity measures – the just noticeable difference JND, transmitted information TI, and the area under the ROC curve, the AUC.

Method

Participants. Twenty five university students volunteered to take part in this study. All of them were healthy with no movement disorders or ankle injury in the 6 weeks preceding the study and were reported to be right foot dominant.

Apparatus. The Active Movement Extent Discrimination Apparatus (AMEDA) was employed for data collection. The AMEDA consisted of two wooden blocks (410 mm × 410 mm × 410 mm from the floor) which provided a platform for a participant to stand on. One wooden board was fixed while the other rotated along the long axis of the foot which could be moved with the inversion movement of the foot until it was stopped by a wooden block placed below on the outer edge of the board. The wooden blocks of three different heights were designated as Shallow (8°), Mid (11°), and Deep (14°). A single block was used for a test series, because with these blocks, different stop-heights could be tested with active inversion of the foot by use of five aluminium spacers with different thickness (1 mm–5 mm) that could be slipped in underneath the wooden block, and by including the 'no spacer' possibility, six different inversion depths were able to be generated for each of the three blocks. The angular depth (S: stimulus) for a corresponding metal spacer and the range for each depth is show in Table 1.

Table 1. Angular depth of each stimulus (S) and the range of each condition.

	S1	S2	S3	S4	S5	S6	Range
Shallow (8°)	8.21	8.55	8.90	9.20	9.54	9.90	1.69
Middle (11°)	10.82	11.16	11.52	11.82	12.16	12.52	1.70
Deep (14°)	13.87	14.21	14.58	14.88	15.23	15.59	1.72

Procedure. The participant stood on the AMEDA with the tested foot on the movable board. Upon a 'go' signal, a steady ankle movement was produced until the edge of the board was stopped by the wooden block. The participant returned to the initial horizontal position and gave a number judgment. Familiarisation trials with 6 different depths were conducted, informing the corresponding number of to each depth.

During trials, participants made foot movements, followed by an immediate reporting of a number between 1 and 6 to indicate the depth felt by the extent of movement. The 48 trials for each block were conducted on the right foot in random order, with a 2-min rest between blocks of trials. Maintenance of an even distribution of weight on both legs was visually monitored by the experimenter throughout the trials.

Analysis. The stimulus value on each trial and the corresponding absolute judgement were collected and used for three different analyses to obtain JND, TI, and AUC.

JND: Percentage of greater than standard stimulus (S3) is plotted against variable stimulus values, and probit analysis (Matlab, Mathwork) was used to find the best fit for the cumulative normal curve. With this curve, the just noticeably less (JNL), the stimulus which is judged to be less than standard on 75 per cent of trials, and the just noticeably greater (JNG), the stimulus which is judged to be greater than standard on 75 per cent of trials were calculated. The average just noticeable difference (JND) is calculated by halving the intervals between JNL and JNG:

$$\mathrm{JND}=\frac{|\mathrm{JNG}-\mathrm{JNL}|}{2}. \quad (1)$$

TI: The amount of presented stimuli, response frequency, and joint occurrence of the stimulus-response match can be quantified in bits of information using a confusion matrix. From this matrix, average amount of transmitted information can be calculated as below:

$$T(x; y)=H(x)+H(y)-(x, y), \quad (2)$$

where T(x;y) is the amount of information transmitted from stimulus to response. H(x) is the estimated information-per-stimulus, H(y) is the estimated information per response, and H(x,y) is the estimated information in the joint occurrence of a stimulus and response (Attneave, 1959).

AUC: angle stimuli were considered as noise and signal in a pair-wise manner (1-2, 2-3, 3-4, 4-5, 5-6), and response values to each stimulus pair were treated as a rating scale for the signal and noise presentation (McNicol, 2004). For each consecutive stimulus pair, 1-2, 2-3, 3-4, 4-5, and 5-6, signal and noise correspond to greater and lesser values (Welford, 1976). The Matlab (Mathworks) program was used to calculate the ROC curve.

A repeated-measures ANOVA was conducted on each discrimination measure using SPSS for Windows. Polynomial trend contrasts was used to test for the linear trend in scores across three depths (Shallow, Mid, Deep) for each measure.

Results

Mean JND, TI and AUC values for three different depths are shown in Table 2 and Figure 1. JND values ranged from 1.12° to 1.26°, and average information transmitted ranged from 0.48 to 0.56 bits. Both measures did not show any significant linear trend with depth, $F(1, 24) \leq 2.74$, $p \geq .11$. AUC values ranged from 0.56 to 0.59, and the ANOVA showed a significant linear decrement in discrimination ability as the block depth decreased from Shallow to Deep, $F(1, 24) = 5.17$, $p < .05$. Across the stimulus pairs, the AUC also showed a significant downward linear trend, $F(1, 24) = 4.61$, $p < .05$. Hence, according to the AUC measures, discrimination of ankle inversion angle was significantly more difficult at the deeper positions.

Table 2. Mean (± standard deviation) values of discrimination measures of inversion movement in three depths.

	Shallow	Mid	Deep
JND (°)	1.12 ± 0.89	1.20 ± 0.78	1.26 ± 0.80
TI (bits)	0.56 ± 0.25	0.54 ± 0.13	0.48 ± 0.09
AUC	0.59 ± 0.06	0.56 ± 0.04	0.56 ± 0.04

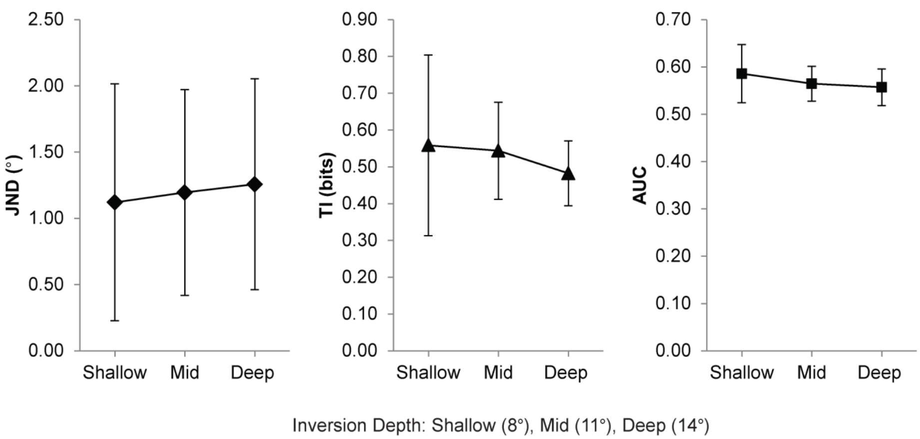

Figure 1. Discrimination measures - JND, TI, and AUC - in Deep Mid and Shallow depth condition. JND: just noticeable difference, TI: transmitted information, and AUC: area under the ROC curve.

Discussion

As the depth increased, mean sensitivity values of all measures tend to decrease, but only AUC measures were able to detect a significant trend of the discrimination ability becoming worse. The significant downward linear trend of AUC measures with increasing movement extent is in line with other previous findings examining the discrimination measures under active (Magill & Parks, 1983) or passive arm movement conditions (Carlton & Newell, 1985), where increase in JND values with movement amplitude were reported. Similarly, in the movement matching task, mid-range of joint angles showed the highest accuracy (Clark et al., 1979). Cattell and Fullerton (1892) also mentioned that the Weber's law does not seem to hold for the perception of movement, but they found rather JND increased proportionally with the square root of the movement extent. All these findings and observations are congruent with the results obtained by AUC measure. Among JND, TI and AUC measures, we might safely assume that AUC method to have the highest sensitivity for measuring movement discrimination ability when using a total of 144 trials of stimulus presentation and the method of absolute judgement.

The number of trials might be one of the reasons why JND did not show a significant difference with depth. In calculating JND, the sensory error of each stimulus is assumed to follow the Gaussian Law of error distribution. To obtain this probability curve, 48 trials for each depth might not have been enough for obtaining the best estimates from the probit analysis. Early studies of JND on movements usually employed around 1,000 trials to obtain reliable estimation of the probability curve (Cattell & Fullerton, 1892; Peirce & Jastrow, 1885). With increased number of trials, we might see similar results between JND and AUC, but the sheer number of trials lacks practicality.

The channel capacity model using the Shannon index is used for the TI measure. This measure represents how much information has been transmitted through the human central nervous system. Our results showed that the discrimination task using method of single stimuli involved around 0.5 bits of transmitted information. In their matching task using proximal interphalangeal joints, Clark and colleagues (1995) found the TI values to be 1.4–1.9 bits. As these studies utilised a total of around 1,000 trials to estimate the probabilities using a confusion matrix, again, the number of trials might have been the limiting factor and the reason why the measure failed to produce significant results.

The AUC measure is calculated using the underlying model of signal plus noise versus noise distribution curves on the sensation continuum. By using presentations of trials and the associated responses, the probability curve for correct detection of the signal, and false alarm rate, are obtained for plotting a ROC curve (Snodgrass, Berger, & Haydon, 1985). The sensitivity of detection represented by this method is the same for one subject regardless of the different criterion used (McNicol, 2004). As the measure can report the expected difference in movement sensitivity with increasing depth, this method is not only sensitive but also practical in its application due to relatively fewer trials involved. Several studies using this method have addressed a wide range of applied questions associated with proprioception sensitivity, such as the issue of limb dominance and proprioception (Cameron & Adams, 2003) or neck proprioception with frequent subclinical neck pain (Lee, Nicholson, Adams, & Bae, 2005). With its practicality and sensitivity, AUC measure will be useful for future studies examining proprioception and motor function by providing a viable tool to quantify movement discrimination ability.

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