Hand-Skin Temperature and Tracking Performance

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ABSTRACT

Even though manual tracking performance has been extensively investigated, there is little or no research related to the lower limit of temperature for unimpaired tracking performance. This study sought to obtain temperature limits while investigating the effect of hand-skin temperature on manual tracking. Eighteen subjects participated in a within-subject design experiment. The hand-skin temperatures corresponded to bath temperatures of 10, 20 and 30 ^{0}C. Tracking performance was measured using the Drury (1971) task of drawing between two continuous straight lines of length 200mm and widths 1.5 mm, 2mm, 2.5mm, 3mm, and 4mm. Performance measures were the time to draw the line and the number of errors as determined by the cross-over points of the drawn line with the printed lines. Both performance measures were consistent and showed significant effects ($p < 0.05$) of line spacing and hand-skin temperature. Performance with bath temperatures of 10°C was significantly worse than that with bath temperatures of 20°C and 30°C.

Keywords: Hand, skin temperature, tracking, cold stress, climate, performance

Relevance to Industry:

Workers are exposed to cold temperatures in numerous ways. Even though personal protective equipment can be used to minimize cold exposure, in tasks such as hand/arm tracking, performance decrements can be quite significant when wearing gloves or other protective equipment. Hence, it is important to identify the cold-limiting temperatures and task characteristics beyond which identifiable decrements of performance exist so that appropriate tasks can be designed for individuals, depending on the existing temperatures.

1. INTRODUCTION

Researchers have long investigated the effects of thermal environments on human health and safety. For example, Ramsey et al. (1983) reported that the least number of unsafe behaviours occur when the wet-bulb globe temperature is between 17 and 23 ^{0} C, which is below the threshold limit value for heat stress and strain (ACGIH, 2004). Fogelman et al. (2005) found an inverted U-relationship between acute injuries and temperature with an increased odds ratio at temperatures below -7 ^{0}C and above 32 ^{0}C. Performance effects in cold conditions have been explored by many (Heus et al. 1995; Nag and Nag, 2007) and some have proposed guidelines for work in cold environments (Holmer, 1994a and b).

Most office or manual work involves some form of tracking with the hands. Even though the effect of temperature on tracking skill has not been investigated, there exists research related to many other manual tasks. People experience cold temperatures as a result of low air or water temperatures, from wind-chill (Pienimäki, 2000) or from touching cooled or frozen products in cold stores (Piedrahíta, et al., 2004). The resulting skin temperatures from cold environments present a health and safety risk in terms of pain and discomfort, numbness, and even skin damage (Daniels 1956; Chen et al. 1994; Enander, 1986; Havenith et al., 1995). When a person is exposed to cold, there tends to be vasoconstriction in the peripheral musculature (Ducarme and Tikuisis, 1991) as well as in the skin (Berne et al. 2004), due to heat loss. As a result, the blood flow to the extremities is reduced even when the hand is exposed to mildly cold temperatures such as 15-25 ^{0}C. (Daanen, 1997). The reduction in blood flow may be the cause for losses in tactile sensitivity (Provins and Morton, 1960), reduced manual performance, grip strength (Holewijn and Heus, 1992; Giesbrecht et al., 1995; Geng 2001, Powell et al., 2000) and increased risk of accidents (Enander, 1984;

Havenith et al., 1995; Heus et al., 1995; Geng et al., 2001). Morton and Provins (1960) have found that tactile sensitivity is an L-shaped function of skin temperature and that each individual has a relatively sharp critical temperature at which performance deteriorates significantly. This reduction in sensitivity makes small-object manipulation difficult. Hence, assembly, typing, and small-repair tasks can be adversely affected by 'cold' temperatures if no proper protection is used. Dexterity is decreased when finger temperatures are less than 16 ^{0}C (Clark, 1961; Havenith et al., 1995; Gaydos and Dusek, 1958) and sometimes even when the hands are air-cooled to 19.1 ^{0}C (Lockhart et al., 1975). Even though Millls (1957), Lockhart and Kiess (1971), and Teichner (1957) have not always found an association between finger dexterity and finger temperature during cold exposure, Brajkovic and Ducharme (2003) found that finger temperature is a more important indicator of finger dexterity compared with finger blood flow.

Onset of pain has been reported when the contact temperature is around 15 ^{0}C (Geng et al., 2006; Malchaire et al., 2002; Havenith et al., 1992, 1995) with a significant deterioration of tactile discrimination when skin temperatures are less than 8 ^{0}C, with numbness in approximately one-third of the subjects at 7 ^{0}C (Morton and Provins, 1960) and a frostbite threshold at a contact temperature of 0 ^{0}C (Geng et al., 2006). Brajkovic et al. (1998) define the comfortable temperature for fingers to be greater than 23 ^{0}C. In this study, we attempted to investigate how hand temperatures of 10, 20 and 30 ^{0}C would affect tracking performance

Oksa et al. (1995) found that muscle performance as measured by mean IEMG activity decreased at a temperature of 10 ^{0}C. Cooling slowed the function of the agonist muscle and decreased its IEMG activity but increased the IEMG activity of the antagonist muscle. Some researchers have reported that the endurance time of sustained, submaximal, voluntary contractions of muscles are temperature dependent, being optimal at peripheral temperatures of 18-26 ^{0}C (Clarke, Hellon and Lind, 1959). In addition, they found that the maximum voluntary tension of muscles was lowered when exposed to temperatures below 20 ^{0}C (muscle temperature below 27^{0}C). However, as outlined by Clarke et al. (1959) and Davies et al. (1982) there are always large temperature gradients between the exterior and muscle interior, especially when testing large muscles such as those on the forearm and leg. In order to overcome this discrepancy, Ranatunga et al. (1987) conducted an experiment on a smaller peripheral muscle, namely the first dorsal interosseus muscle, which allows the abduction of the index finger. For skin temperatures (T_s) in the range of approximately 12 to 40 ^{0}C, they found that the muscle temperature, T_m, measured at a depth of 0.5 -0.7 cm, can be modelled as $T_m = 3.2 + 0.8\ T_s$, implying that the muscle temperature closely follows the skin temperature of the finger.

All the aforementioned studies are confirmations of the detrimental effects of muscle cooling on force, power and contraction velocities, but more recently researchers such as Geurts et al. (2004) have shown that cooling reduces physiological tremors and can thereby improve force control during precision movements. A tremor is defined as “an involuntary, rhythmic, oscillatory movement produced by reciprocally innervated antagonist muscles” (Anouti and Koller, 1995). The Geurts et al. finding may possibly be a good explanation for the differential effects of thermal discomfort on rifle marksmanship. Lakie et al. (1994) showed that temperature has an effect on tremor size and that moderate cooling of the forearm greatly reduces wrist tremors (Lakie et al., 1995), which are high-frequency, low amplitude shaking with a peak frequency between 7 and 11 Hz (Findley and Gresty, 1984). In a subsequent study, Lakie et al. (1995) were primarily driven by reduction of tremors and found that the accuracy of shooting increased with forearm cooling. The subjects in Lakie et al.’s (1995) study immersed their hands for 10 minutes in water at either 10 ^{0}C or 44 ^{0}C. They found that the accuracy of the horizontal component, but not the vertical component, was affected by heat. Reading et al. (1998) found that the horizontal deviation of shots fired at a stationary target increased by 21% when the subjects were exposed to cold (4.4^{0}C) compared with neutral conditions (23.9 ^{0}C). Tikuisis et al. (2002), however, did not find any degradation in performance as long as the deep body temperatures of their subjects were between 37.9 ^{0}C and 36.4 ^{0}C and their hand temperatures were not less than 19 ^{0}C. Surprisingly, they found the horizontal displacement and accuracy measured as shooting error were poorer when the body was in a neutral condition (22 ^{0}C) compared with hot (35 ^{0}C) or cold (5 ^{0}C) conditions. Whether the differences or the lack of differences at this wide range of temperatures used in these studies is due to variations in thermal stress or thermal strain is not clear. Thermal stress is the heat or cold the subject experiences whereas thermal strain is the resulting change in the body heat content and temperature due to the stress. This differentiation is important as different levels of thermal strain can be attained at the same environmental conditions, depending on the amount of personal protective equipment used and the level of activity in which the person is involved. Geurts et al. (2004) provide a reasonable explanation for the possible differences among the studies. Cooling the hand causes numbness in fingers (Morton and Provins, 1960) and reduces sensory feedback. In the Lakie et al. (1995) study, the forearm muscles were cooled rather than the hand and hence tactile discrimination may not have been altered even though the contractile characteristics of the forearm muscle changed and reduced the physiological tremor, thereby improving shooting performance and even fine motor skills such as writing or drawing the Archimedes spiral (Cooper et al., 2000) in subjects with essential tremor (Lakie et al., 1994).

Hand exposures to cold temperatures can be reduced through the use of gloves or other forms of protection. However, dexterity associated with small part manipulations and assembly does reduce with the use of gloves (Bishu et al., 1987). Some have reported decreases of finger dexterity by as much as 60-70% (Brajkovic et al., 2001; Havenith and Vrijkotte, 1993). At the same time, Brajkovic et al. (2001) did not find any difference between bare hands and gloved-hands in a C-7 rifle assembly and disassembly task and declared that gross finger dexterity tasks are not as affected as fine finger dexterity tasks such as the Purdue pegboard test. Tracking can be considered to be a fine dexterity task depending on the track widths. It is thus important to find the lower limit of temperature that hinders motor skills without any hand covering (bare hands). Even though Sanders and McCormick (1992) state that the lower limit for unimpaired tracking is still uncertain, they suggest an ambient temperature of 4 to 13 ^{0}C (39 to 55 ^{0}F).

The primary objective of this study was to investigate the relationship between tracking performance and hand-skin temperature. The task used was tracking within a constraining path as designed by Drury (Drury, 1971; Drury, Montazer and Karwan, 1987). This model has been shown to be applicable to many types of tracking tasks within a constrained path, such as fork-lift truck driving (Drury and Dawson, 1974), motor-vehicle driving (DeFazio, Wittman and Drury, 1992), wheeling trolleys through corridors (Drury, Barnes and Daniels, 1975) and control of a cursor on a computer monitor (Accot and Zhai, 1997). Drury's theoretical model (1971) posits that the movement time (MT) and the speed of movement (V) are dependent on the distance moved (A) and the width of the constraining path (W):

$$MT = a + b\,(A/W) \text{ and } V = c + d\,(W),$$

where a, b, c and d are empirically determined constants.

2. METHODOLOGY

2.1 Subjects

Eighteen volunteer participants were recruited for this within-subject study design. None of the participants had any hand or other physical defects. This study was approved by the university research ethics committee on human subjects.

2.2 Procedure

The ambient temperature was 22 ^{0}C. Three temperature-controlled water baths, maintained at 10°C, 20°C, and 30°C, were used to alter the participants' skin temperatures. The effects of cold water between 15 and 25 ^{0}C on forearm, hand and finger temperatures has been studied by Ducharme and Tikuisis (1991, 1992); Tikuisis and Ducharme (1991); Lindsell and Griffin (2001); Suizu and Harada (2005). An ambient temperature of 21 ^{0}C and a water temperature of 15 ^{0}C resulted in a finger temperature of 15.5 ^{0}C, whereas an ambient temperature of 24 ^{0}C resulted in a finger temperature of 22.1 ^{0}C (Ducharme and Tikuisis, 1991, 1992; Tikuisis and Ducharme, 1991; Lindsell and Griffin, 2001; Suizu and Harada, 2005).

Each subject was asked to dip his/her hand in a temperature-controlled water bath for 1 minute. Finger skin temperatures decrease quite rapidly. In previous studies, it was found that when touching aluminium and steel at -4 ^{0}C, skin temperatures of 0 ^{0}C were measured within 15 to 20 s of contact and the onset of cold pain was reported within 5 s of contact with non-metallic surfaces at -20 ^{0}C (Geng et al., 2006). Morton and Provins reported that the finger temperature of their participants dropped to -5 ^{0}C in approximately 3-4 min. In other words, at a rate of around 10 ^{0}C/min. Hence, the short exposure of 1 min may be sufficient to reduce the finger/hand temperature to the modelled muscle temperature of $T_m = 3.2 + 0.8\ T_s$

as suggested by Ranatunga et al. (1987). The hand-skin temperature was not measured in this experiment but past research has suggested that the hand-skin temperature can be assumed to be close to the water bath temperature.

Subjects were divided into three groups of six. Each group performed the three temperature tests in a different balanced order. The subjects were given a 5-minute break between each temperature condition. Tracking performance was measured, using the Drury (1971) task, by the subject drawing a continuous line between two straight lines from left to right, using a pencil in his/her preferred hand. After dipping the hand into a bath of a given temperature for 1 minute, each subject was asked to draw 5 lines 200 mm in length between two printed lines set apart at different widths. The widths between the two lines were set at 4mm, 3mm, 2.5mm, 2mm, and 1.5mm. The order in which each width was presented to each subject was randomized. Each subject drew 15 lines corresponding to the three water temperatures and five lines for each temperature. The subjects were asked to draw each line as fast and accurately as possible.

3. RESULTS

Performance measures were the time to draw a line 200mm in length with a given spacing (4, 3, 2.5, 2, 1.5mm) and the number of errors as determined by the cross-overs of the drawn line with the printed lines. In all regressions, normality of the residuals was tested with the Anderson-Darling measure; in all cases, the residuals satisfied the normality test.

3.1 Analysis of Movement Times/Speed of Movement

A normality test of the data indicated the need for a logarithmic transformation (Anderson-Darling test, $p>.05$). This requirement is seen in the variation of the standard deviations with the mean values of Table 1. Transformed data showed homogeneity of variance across all variables (Cochran's test, $p > .05$). A within-subjects ANOVA showed significant main effects of path width [$F(4,68) = 54.46$; $p < .001$] and temperature [$F(2,34) = 3.43$; $p < .05$]. There was no significant interaction between these variables with the transformed data. Newman-Keuls post-hoc tests showed that there were significant differences between 10 degrees and 20/30 degrees in the time taken for the task ($p < .05$). Movement time increased with decreases in the path width and all comparisons were significant (most at $p < .01$) except for the comparison between 2.5 and 3 mm, which was not significant. There is thus a very clear pattern of the effects of hand temperature on movement time. Data are shown in Table 1, in Figure 1, and in the alternative form of Drury's model (speed as a function of path width) in Figure 2. A breakdown of the data into track widths showed that only at the two smallest track widths was there a significant effect of the bath temperature on the movement time.

Insert Table 1, Figures 1 and 2 about here

Regressions of the mean data in terms of Drury's model for movement through constraining paths (MT in sec., V in mm/sec), were as follows:

$MT\ (10) = 0.587 + 0.0213\ A/W;\ r^2 = .95$

$MT\ (20) = 0.679 + 0.0163\ A/W;\ r^2 = .98$

$MT\ (30) = 0.867 + 0.0130\ A/W;\ r^2 = .88$

$V(10) = 13.0 + 29.3\ W;\ r^2 = .96$

$V(20) = 28.9 + 27.9\ W;\ r^2 = .99$

$V(30) = 34.3 + 27.3\ W;\ r^2 = .94,$

where the 10, 20 and 30 refer to the temperature in ^{0}C. It is seen that the model gives an excellent description of the data.

3.2 Analysis of path tracking errors.

A tracking error was considered to have occurred when the pencil moved outside the defined path. Data were transformed using a square-root transformation to achieve normality of the data (Anderson-Darling test, $p>.05$). The transformation achieved homogeneity of variance within conditions (Cochran's test, $p>.05$). A within-subjects ANOVA of these errors showed a significant main effect of path width [$F(4,68) = 32.64$; $p<.001$]. The temperature was not significant in the analysis using transformed data. Newman-Keuls post-hoc tests showed that errors increased with decreasing path width; all comparisons were significant at $p<.01$, apart from those for the two widest path widths, which did not show a significant difference in errors. The pattern of errors is shown in Figure 3, again as a function of the ratio (A/W). A breakdown of the data into the various track widths showed that only at the smallest width was there a significant effect of the temperature on the number of errors.

Regression of the mean data, in terms of the errors per unit distance traveled, showed no linear effect of (1/W), a strong quadratic effect and no significant intercept. The data are well represented by (these regressions account for at least 93% of the variance)

$\text{Error}\ (10)/A = 0.0718 / W^2$

$\text{Error}\ (20)/A = 0.058 / W^2$

$\text{Error}\ (30)/A = 0.0468 / W^2\ .$

The parabolic pattern is clearly discernable in Figure 3. The gradient of the relationship between errors and $(1/W)^2$ is given by

Gradient = 0.0838 - 0.0012 (Temperature); $r^2 = .99$.

The relationship between errors per unit distance moved; the path geometry and the temperature is then well represented by

Error per distance = (0.0838 - 0.0012 Temperature) / W^2

Insert Figure 3 about here

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4. DISCUSSION

The ANOVA results show a significant decrease in tracking performance as measured by movement time (or speed), but not a significant effect on the number of errors, when the hand-skin temperature is 10°C. This decrease in performance is shown by post-hoc tests to be a continuous decrease in movement speed as the track width decreases. The effect of the bath temperature was confined to the two smallest track widths for the movement time and to the smallest track width for the number of errors. These results are similar to those of the gross finger dexterity and fine finger dexterity seen in other studies, such as that by Brajkovic et al. (2001), where there were no differences in a C-7 rifle assembly and disassembly task with bare hands and gloved hands. The effects of the reduced hand/skin temperature are clearly in the reduction in fine motor control. The Sanders and McCormick (1992) recommendation of an ambient temperature of 4 to 13 ^{0}C seems to be appropriate for gross tracking where the track widths are relatively large. But, with an ambient temperature of 4 to 13 ^{0}C it may also be possible that the accuracy may improve as the tremors reduce due to a reduction in forearm temperature (Lakie et al., 1994, 1995). When only the hands are cooled, both time and errors seem to be impaired at a temperature of 10 ^{0}C with smaller tracks. The results are in line with the physiological changes as well. At 10 ^{0}C, the hands are relatively cold, and are below the threshold of pain (Geng et al., 2006; Malchaire et al., 2002; Havenith et al., 1992, 1995). Gaydos and Dusek (1958) found a significant decrease in finger dexterity at a finger temperature of 10-13 ^{0}C. Lockhart et al. (1975) reported significant decrements in psychomotor tasks such as block stringing, knot tying, screw tightening and on the Purdue pegboard when the back of subjects' hands were air cooled to 19.1 ^{0}C. Tikuisis et al. (2002) attributed the decrement in performance in psychomotor tasks to a possible loss of dexterity at the low temperature. Cooling the hand even for such a short time reduces the sensory feedback and that may have caused the higher errors and increased task time, possibly due to a higher force application on the pencil (though the forces were not measured). The higher force could have resulted in a reduced blood flow and a further loss of sensation.

Even though the Archimedes spiral is common tool for the assessment of tremor (Cooper et al., 2000; Lakie et al., 1994), the Drury (1971) tracking task appears to be a sensitive task with which to measure some effects of reduced hand temperature on performance, specifically where a tracking task is performed that requires good control for accuracy. Drawing the Archimedes spiral requires a large amount of wrist movement due to its two-dimensional nature and especially with patients having pathologic tremor (Cooper et al., 2000); a straight line tracking task may be one that can be used to identify the tremors of the larger muscle groups in the arm. More importantly, pathologic tremor is identified from the Archimedes spiral drawing using a scale of 0 to 3 (0=no tremor; 1=barely visible tremor; 2=readily apparent tremor; 3=severe tremor) (Cooper et al., 2000), which is a rather gross classification. With the use of the Drury tracking task and corresponding model, a finer distinction of the level of tremor may be possible for early diagnosis of tremor-related illnesses.

The effects of temperature on errors appear to be approximately linear in the range of 10 to 30 ^{0}C. The effects on movement time and speed are not so easy to quantify, due to the differing gradients with temperature. In the speed form however, the gradients are similar for the three temperatures, and the intercepts are dependent on the temperature. Relative to a temperature of 20 ^{0}C, the performance at 10 ^{0}C can be modeled approximately as a decrement of 11 mm/s and that at 30 ^{0}C as a positive increment of 5 mm/s. The corresponding data are shown in Figure 4, with these temperature increment effects included.

Insert Figure 4 about here

There is no doubt that the time restriction of having the hand immersed for only one minute is a limitation in this study. Considering that, in the Mortons and Provins (1960) study, finger temperature dropped to -5°C in approximately 3-4 minutes, we know that finger temperature does reduce quite rapidly. In addition, the fact that there was a significant decrement in performance at 10°C does indicate that even a short exposure of the hands to cold water temperatures is detrimental. Wearing gloves may be a possible way to reduce the performance decrement at low temperatures. However, it should also be noted that wearing gloves will increase the muscular load requirement for a given task and will also hamper handling small objects as tactile sensitivity is reduced (Buhman et al., 2000). The effects of using gloves or other suitable protection as a safety measure needs to be determined, because although gloves may protect hands against damage, they may well have an effect more detrimental to tracking performance than the lower temperature has, as finger dexterity has been found to be seriously impaired with gloves (Bishu et al., 1987; Brajkovic et al., 2001; Havenith and Vrijkotte, 1993). The hand-skin temperature will be slightly higher than the bath temperature due to the relatively short immersion time; the results need to be considered in terms of this limitation. However, the temperature reported in this paper has practical significance as finger temperature is not easy to measure.

To conclude, it may be said that the Drury tracking task and the model are quite appropriate to use even at low temperatures. It also seems to have significant advantages over the Archimedes spiral, which is commonly used to identify pathologic tremor in patients, as it would be possible to diagnose patients at an earlier time with a finer performance measure.

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Table 1. Average movement times (sec) and number of errors for the five path widths used in the experiments. The numbers 10, 20 and 30 refer to the temperature. Bracketed numbers are standard deviations of the movement times and number of errors.

Width	**A/W**	**MT(10)**	**MT(20)**	**MT(30)**	**Error(10)**	**Error(20)**	**Error(30)**
1.5	133.3	3.32(1.21)	2.79(1.05)	2.52(1.19)	6.56(2.62)	5.33(2.31)	3.94(1.74)
2.0	100	2.83(1.27)	2.37(.87)	2.19(.88)	3.28(1.82)	2.55(1.49)	2.55(1.24)
2.5	80	2.29(.88)	2.04(.72)	2.05(.80)	2.33(1.90)	1.61(1.42)	1.44(.86)
3.0	66.7	2.15(.75)	1.79(.65)	1.84(.66)	1.50(1.38)	1.39(1.25)	1.22(1.07)
4.0	50	1.48(.45)	1.42(.66)	1.34(.42)	1.00(1.37)	1.33(.86)	1.00(.70)

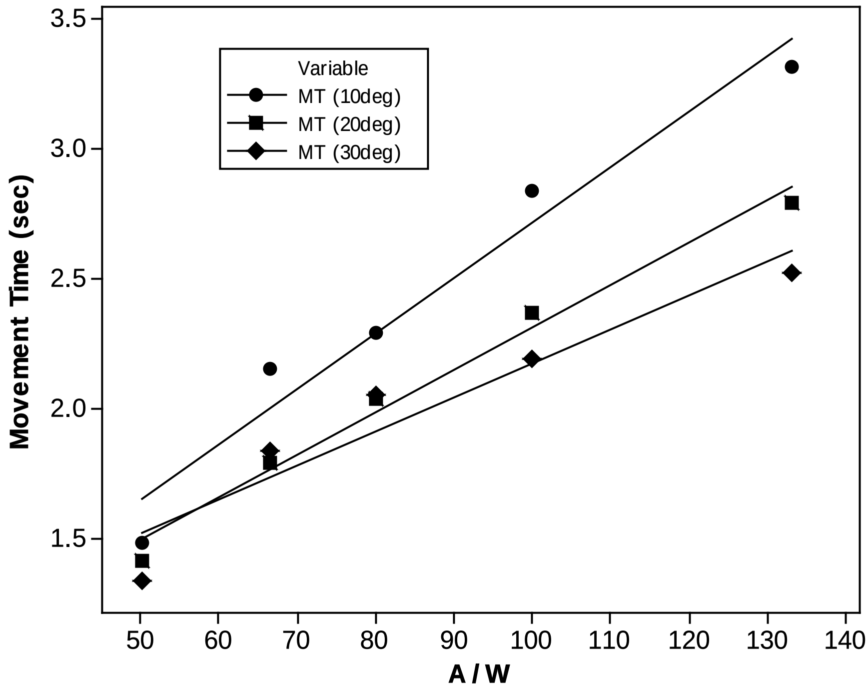

Figure 1. Movement time through the constrained path modeled in terms of Drury's law, showing the effect of temperature.

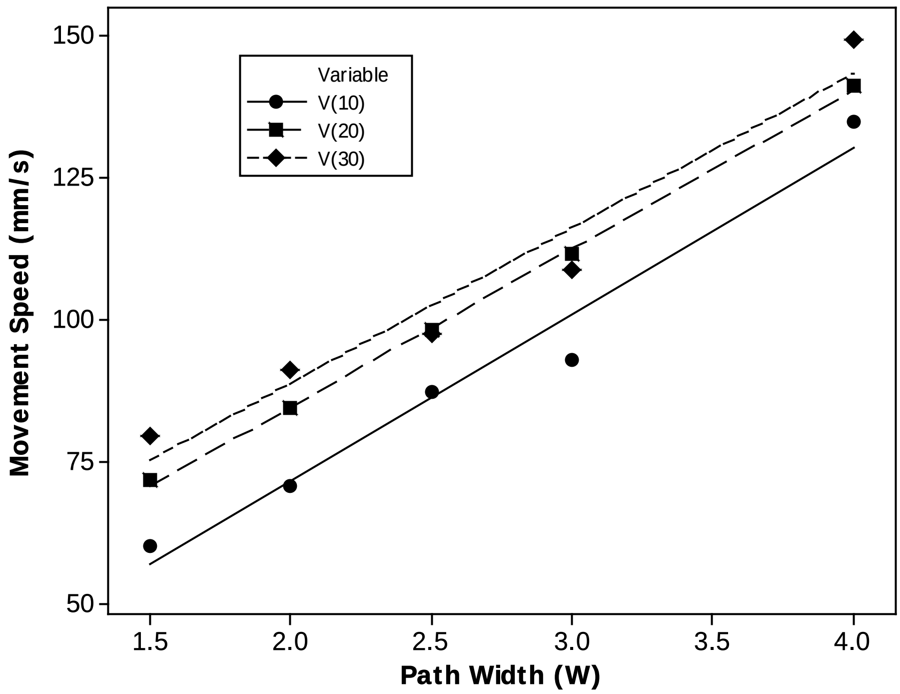

Figure 2. Same data as Figure 1, but plotted in the velocity form of Drury's law, again showing the effect of temperature.

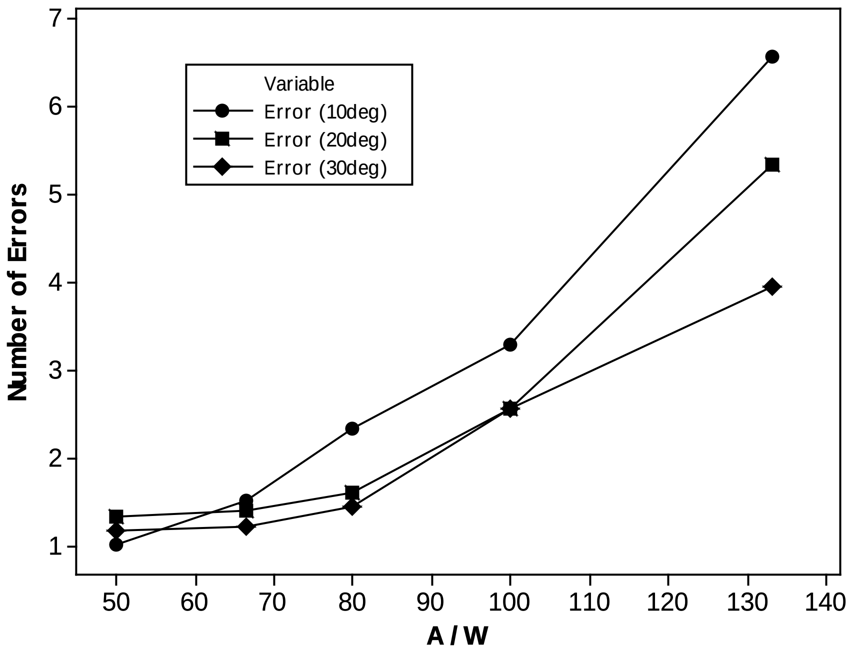

Figure 3. Errors as a function of the (A/W) ratio and dependent on temperature.

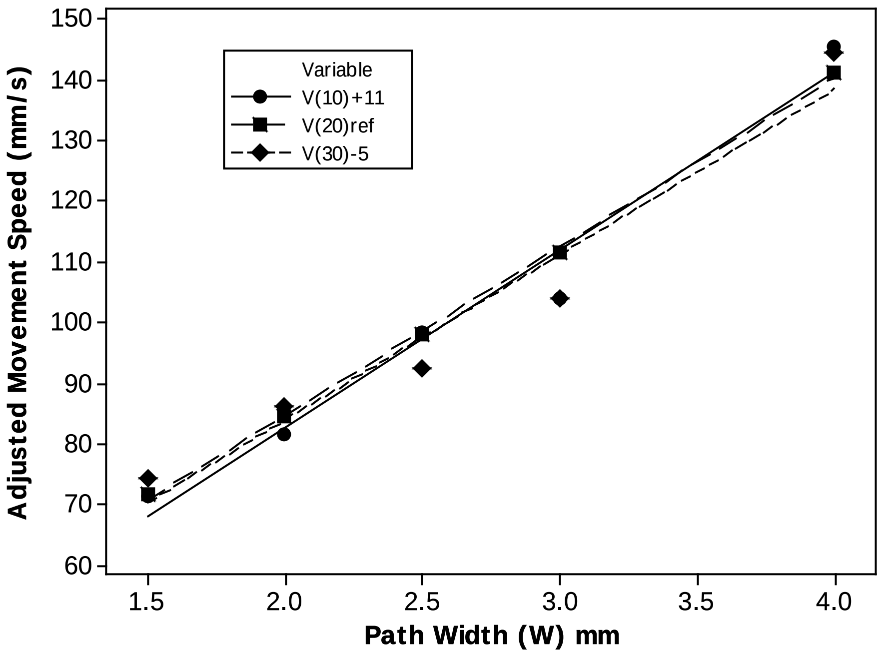

Figure 4. Speed as a function of path width in the Drury tracking task showing the dependency on temperature through an incremental effects of temperature (a decrement of 5 mm/s at 10 deg C and an increment of 11 mm/s at 30 deg C)