Compensatory properties of visual information in the control of isometric force

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This experiment investigated the effects of spatial (gain) and temporal (frequency) properties of visual feedback on the control of isometric force output. Participants performed an index finger isometric force production task with five different levels of visual gain and four feedback frequencies. There was a significant effect of gain on mean and standard deviation (*SD*) of the force output, whereas feedback frequency significantly affected the force *SD* and root-mean square error. Significant effects of gain and frequency and a gain $\times$ frequency interaction on the approximate entropy (ApEn) of the force revealed the effect of visual feedback uncertainty on the force fluctuation dynamics. The combined effects of the spatial and temporal properties of visual feedback on ApEn were approximated by a sum of quadratic functions, indicating their compensatory effect on the informational content of the dynamics of isometric force.

At least since Woodworth (1899), there has been continued interest in the role that visual information plays in the control of human motor performance (cf. Carlton, 1992; Desmurget & Grafton, 2000; Elliott, 1990). A classic paradigm is that of manual control, in which “a person is receiving through his senses (visual, vestibular, tactile, etc.) information about the ideal states of some variables of a given system, as well as the output states of those variables, separately or in combination” (Sheridan & Ferrell, 1974, p. 171). In this theoretical and experimental framework, visual information is interpreted as reducing the uncertainty of the motor output in relation to the task goal, as reflected in the tenets and indices of information theory (Fitts, 1954; Shannon, 1948). Such a reduction in uncertainty through the presence of visual information of force output can be manipulated by variations of the delay, gain, intermittency, and frequency filtering of the force or movement output (Jagacinski & Flach, 2003).

One experimental test of information theory in manual control has been the manipulation of visual gain of the force output on the screen display (Beuter, Haverkamp, Glass, & Carriere, 1995; Newell & McDonald, 1994; Stephens & Taylor, 1974). Here, it has been shown that enhancement of gain (pixel/Newton ratio; p/N) up to some level improves performance beyond which the performer cannot take advantage of the more precise information, and may even lead to a performance decrement (Newell & McDonald, 1994). The findings from these studies suggest that there is some optimal level of gain for the experimental condi-

tions that more generally can be interpreted as an effect of visual angle, because viewing distance is constant in most studies of gain (Vaillancourt, Haibach, & Newell, 2006). This inverted-U pattern of findings for performance and visual gain parallels that for the effect of the precision of knowledge of results (KR) on discrete response outcome (Newell & Kennedy, 1978; Rogers, 1974).

Sosnoff and Newell (2006) found that manipulation of gain affects both the distributional and dynamic properties of isometric force output. A high number of p/N would mean that 1 N of force is presented over a larger area of the display, and thus, the feedback is more precise. Increasing visual gain resulted in higher standard deviations (*SDs*) and coefficients of variation, leading to an increase in magnitude of variability. As a means of analyzing the properties of the force output dynamics, *detrended fluctuation analysis*, an alternative method of determining the self-similarity or fractal dimension (analogous to the spectral slope) of a nonstationary time series, was employed. This analysis revealed that greater visual gain did not necessarily lead to increased low-amplitude, rapid fluctuations in force. Rather, a U-shaped function emerged, where the middle gain level, approximately 128 p/N , resulted in the greatest proportion of high-speed fluctuations. In an informational framework, these findings would suggest that the amount of information required to capture the fluctuations is greatest at the intermediate gain levels.

Whereas gain alters the precision of visual feedback spatially, intermittency of feedback changes its precision

temporally. Prior studies that have employed intermittent visual feedback in precision walking have found that increasing the frequency of visual feedback allows for a reduction in errors as well as the total movement time (Assaiante, Marchand, & Amblard, 1989; Robertson, Collins, Elliott, & Starkes, 1994). Similarly, Elliott, Zuberer, and Milgram (1994) found, in a ball-catching task, that a reduction in time between presentations of visual feedback samples resulted in an increased probability of making a successful catch.

Using an intermittency paradigm of the frequency of visual feedback complementary to that of Miall (1996), Slifkin, Vaillancourt, and Newell (2000) found that decreasing visual feedback frequency (i.e., a reduction in the rate at which visual feedback is presented to the participants) led to an increase in magnitude of variability and a decreased ability to track the target force level in a constant isometric force production task, and thus, greater error. This effect of visual feedback frequency has proven to be robust during different percentages of maximal force in the constant force task (Sosnoff & Newell, 2005b) and is upheld in rhythmic (sine wave) isometric force production tasks (Sosnoff & Newell, 2005a). Across these studies (Slifkin et al., 2000; Sosnoff & Newell, 2005a, 2005b), an analysis of predictability within the force output fluctuations using *approximate entropy* (ApEn; Pincus, 1991) revealed that decreasing feedback frequencies resulted in greater predictability within the force time series. Thus, one could infer from the increased occurrence of errors with decreasing feedback frequency that greater predictability within the force time series is a reflection of fewer error corrections being made during the trial.

In summary, the greater the amount of visual information provided within a unit of time, the higher the amount of information that will be required in order to describe the dynamics of the fluctuations in isometric force. The studies of the effects of feedback frequency show that a greater amount of visual information in a smaller amount of time leads to more bits of information being required to describe the force output dynamics. Continually increasing the amount of space over which information is presented, however, does not lead to a similar result. Rather, it is possible that an optimal range is preferred by participants. Little, however, is understood regarding the combined effects of both the spatial and temporal properties of visual information on isometric force control, because typically only one of the variables is normally manipulated, with the other held constant at some arbitrarily arbitrary parameter level.

It is relevant that in an analogy to the present problem, de Ruyter van Steveninck, Bialek, Potters, Carlson, and Lewen (1996) have found the spiking rate of the blowfly neuron that is responsible for motion detection to respond to both contrast and velocity of a visual display. By presenting a set of moving bars on a screen and altering the speed at which they moved side to side, as well as the contrast of these bars to the background, de Ruyter van Steveninck et al. were able to elicit different firing rates from the neuron. The result was a compensatory effect of velocity and contrast, where high levels of contrast with low velocity

resulted in firing rates that were equivalent to those of high velocities with low background contrast. de Ruyter van Steveninck et al. then employed a surface generated with a quadratic function as a means of capturing the relationship between spike rate and contrast and velocity. This function peaked at the highest levels of contrast and velocity, suggesting a convergence of functions of change in neuronal spike rate with contrast and velocity. This finding highlights the mutuality and complementary nature of visual information sources in neuronal firing rates, which raises the possibility that mutual information is contained within the spatial and temporal properties of visual information used to control a motor output.

The goal of this study is thus to investigate the role of visual feedback manipulations on the informational content of muscle force output dynamics. Here, we systematically manipulate the gain and frequency of visual feedback as sources of spatial and temporal information. One of the main reasons for employing an isometric force production task is that the control of the force to the target level generated by the index finger cannot be guided by proprioceptive and tactile feedback alone (Sosnoff & Newell, 2005a).

Realistically, the experimenter does not have direct control over the amount of information used by the participants for motor control. Thus, manipulations of gain and feedback frequency should be viewed as changes in the uncertainties in the spatial and temporal domain that can be obtained from the likelihood that no information is present (Shannon, 1948). As such, uncertainties can be calculated on the basis of the probability of occurrence from the limits of the visual system and the display size. On the basis of the findings on the combined effects of velocity and contrast of de Ruyter van Steveninck et al. (1996), it was hypothesized that spatial and temporal uncertainty will have similar compensatory effects on the informational content of the motor output.

METHOD

Participants

Twelve (6 female and 6 male) right-hand-dominant (determined by preferred writing hand) adults between the ages of 19 and 33 years (mean age 23.8 years) participated in the study. All of the participants had normal or corrected-to-normal vision and no history of neuromuscular disorders. The participants provided informed consent prior to participation, and the experimental protocol was approved by the Pennsylvania State University Institutional Review Board.

Apparatus

A 3-D load cell (ATI Industrial Automation, Garner, NC) was used to measure the force output. The normal force (F_z) produced by the finger was the focus of the analyses, because the task goal was to control this dimension of force.

Procedures

Estimation of maximal voluntary contraction (MVC). MVC for each participant was determined at the beginning of the experimental session. Participants were instructed to exert maximal isometric force by pushing their index finger against the surface of the load cell as hard as they could. Force was generated by pushing against the load cell toward the midline of the body. Each participant completed 2 MVC trials of 10 sec, with a 20-sec rest between each

trial. The average of the highest force value produced in each trial determined the respective MVC for each individual participant.

Experimental design and instructions. Following the determination of MVC, each participant was asked to match their force output to a red target line, which was 25% of their MVC, which appeared onscreen against a black background. The computer monitor on which the visual feedback was provided had a screen resolution of 800 (width) $\times$ 600 (height) pixels. Online feedback regarding force output was provided via a force trajectory (plotted with white pixels) that passed from the left to the right of the screen as the trial progressed. Upon completion of each trial, participants were provided with the root-mean square error (RMSE) as posttrial feedback. RMSE was calculated as

$$\text{RMSE} = \sqrt{\frac{\sum (F - f_i)^2}{(n-1)}}, \quad (1)$$

where F is the target normal force value and f_i is the i th force sample in the time series.

Gain of the visual feedback was manipulated through the p/N ratio, which altered the precision of visual feedback provided. Five different gain conditions were employed, with visual scales of 512, 256, 128, 32, and 2 p/N. These values correspond to the key conditions in Sosnoff and Newell (2006), which were most representative of the motor information transmission function with visual gain. Each of these gain levels was paired with four different visual feedback frequency conditions at 0.4, 3.2, 12.8, and 25.6 Hz (Slifkin et al., 2000), yielding a total of 20 independent conditions. The conditions were presented to the participants in random order, and participants completed three blocked trials in each condition. An illustration of the manner in which gain and feedback frequency alter the spatial and temporal precision of the visual feedback on the display can be seen in Figure 1.

Data analysis. Effects of the transitory forces at the beginning of the trial and the anticipation of trial termination were removed by omitting the initial 4 sec and the final second of each trial from the analysis. The cropped raw data were then filtered with a digital ninth-order Butterworth low-pass filter with a cutoff frequency of 30 Hz. From the cropped and filtered Fz force time series from each of the trials, mean, SD , and ApEn values were obtained. RMSE values were calculated for the normal force, F_z , as a measure of the participants' performance—namely, the ability to closely track the target force. Gain $\times$ frequency (5×4) repeated measures ANOVAs were run independently on the four dependent variables using STATISTICA (Statsoft, Tulsa, OK). Where necessary, the Greenhouse–Geisser adjustment was applied to correct for any violations of the sphericity assumption.

ApEn was originally proposed as a measure of signal complexity or irregularity (see Pincus, 1991). The ApEn algorithm counts the relative recurrence of vectors of length m , $C_m(r)$, to that of vectors of length $m + 1$, $C_{m+1}(r)$, within a tolerance range of r , as presented in Equation 2. The final ApEn value is the natural logarithm of the ratio of $C_m(r)$ to $C_{m+1}(r)$. ApEn is also a measure of uncertainty (Beltrami, 1999) and thus, in order to create a uniform informational metric, the logarithm base will be altered to 2, to provide the ApEn values in bits. As recommended by Pincus (1991), the value of m was set at 2, whereas r was set to .2 of the SD of the time series

$$\text{ApEn}(\bar{X}, m, r) = \log_2 \left[\frac{C_m(r)}{C_{m+1}(r)} \right]. \quad (2)$$

Generally, in regular/predictable time series, values of $C_m(r)$ will be similar to $C_{m+1}(r)$. Thus, smaller values of ApEn describe a more regular time series, in which similar patterns follow one another, and a low amount of information is required to capture the dynamics of the force fluctuations. Higher ApEn values indicate a more irregular time series, in which the predictability of subsequent events or patterns in the data is low and is reflective of a higher amount of information content and a greater level of uncertainty in the motor output.

Figure 1. This figure illustrates the manner in which a force trace will become altered with different levels of gain and feedback frequencies. The extreme gain and frequency conditions of 512 p/N and 2 p/N at 25.6 Hz and 0.4 Hz are represented. The lower panels are illustrations of a display with a screen height of 600 pixels, but only the 10-sec cropped data that would have been used for the analysis are presented.

In order to convert gain and frequency into an information theoretic framework, *information entropy* or *uncertainty* measures were obtained from the p/N ratio and feedback frequencies. Information entropy (Shannon, 1948), H , is calculated as:

$$H = \log_2 \frac{1}{p}, \quad (3)$$

where p is the probability of occurrence, assuming that all events or symbols have an equal likelihood of occurring. Here, visual gain is represented as *spatial uncertainty*, where increased gain provides more information and thus covers a larger portion of the computer monitor. The higher the gain level, the lower the spatial uncertainty. A display resolution of 800 $\times$ 600 pixels yields the possibility of 600 pixels available for the provision of visual information at any given point in time. The probability, p , can then be estimated as the ratio of gain in p/N to that of the total number of pixels available at a single point in time. Spatial uncertainty at each level of gain will then be $\log_2(600/\text{gain})$. The visual gain levels of 512, 256, 128, 32, and 2 p/N provide spatial uncertainty values of 0.2, 1.2, 2.2, 4.2, and 8.2 bits, respectively.

Frequency is represented as *temporal uncertainty*, because the feedback frequencies result in gaps of different sizes between each presentation of the force output point on the display. As such, lower feedback frequencies result in greater temporal uncertainty. This

Table 1
Summary of Results Obtained From the Repeated Measures ANOVAs Run on the Four Dependent Variables

Dependent Variable	Gain		Frequency		Gain $\times$ Frequency	
	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
Mean	4.78	.0027**	0.36	.7848	0.54	.8846
<i>SD</i>	3.42	.0162*	12.78	<.0001***	1.75	.0629
RMSE	1.52	.2120	23.93	<.0001***	1.65	.0848
ApEn	9.15	<.0001***	54.21	<.0001***	3.33	.0003**

* $p < .05$. ** $p < .01$. *** $p < .0001$.

uncertainty will be estimated on the basis of the boundary conditions of the maximal capacity of the human eye. From Landis (1954), the positioning of the participants with respect to the monitor will yield a critical flicker-fusion threshold (FFT) of approximately 36 Hz, due to a 3° visual angle. The critical FFT is the frequency at which a flashing dot presented to participants becomes indistinguishable from a continuous, steady presentation. Therefore, temporal uncertainty was estimated as $\log_2(36/\text{frequency})$. The visual feedback frequencies of 0.4, 3.2, 12.8, and 25.6 Hz provide temporal uncertainty values of 6.5, 3.5, 1.5, and 0.5 bits, respectively.

RESULTS

Repeated measures ANOVAs revealed significant main effects of visual feedback gain on the mean [$F(4,132) = 4.78$, $p = .0027$] and *SD* [$F(4,132) = 3.42$, $p = .0162$] of the force produced. The main effect of frequency was significant for the dependent variables of *SD* [$F(3,132) = 12.78$, $p < .0001$] and RMSE [$F(3,132) = 23.93$, $p < .0001$]. For ApEn, both main effects of gain [$F(4,132) = 9.15$, $p < .0001$] and frequency [$F(3,132) = 54.21$, $p < .0001$] were significant, along with the gain $\times$ frequency

interaction [$F(12,132) = 3.33$, $p = .0003$]. The *F* and *p* values for the main effects and interaction obtained from the statistical analyses are summarized in Table 1.

Tukey post hoc comparisons of the levels of the main effect of gain on mean force revealed a significantly ($p < .05$) lower mean force output for the lowest level of gain (2 p/N) in comparison with all the other levels (Figure 2, upper panel). A post hoc analysis of the main effect of gain on *SD* found significantly lower *SD* values at the highest gain level (512 p/N) in comparison with the two lowest gain levels—namely, 2 and 32 p/N (Figure 2, lower panel). The upper panel in Figure 3 shows the results of the Tukey post hoc test on the main effect of visual feedback frequency on the *SD* of the force output. The post hoc test found a significantly higher *SD* for the lowest feedback frequency (0.4 Hz) in comparison with the other levels. Similar post hoc test results were obtained for the main effect of frequency on RMSE (Figure 3, lower panel).

The effect of visual gain on ApEn approximated an inverted-U-shaped curve. As such, the Tukey post hoc analysis did not find significant differences between the highest and lowest levels of visual gain. The Tukey post hoc analysis of the main effect of frequency found that ApEn values differed significantly from one another, with the exception of the two highest feedback frequencies—namely, 12.8 Hz and 25.6 Hz. The post hoc results obtained for the significant main effects of gain and frequency on ApEn are presented in Table 2.

Representations of the gain $\times$ frequency interaction for ApEn can be seen in Figure 4. The upper panel presents the effect of visual gain on ApEn at the different feedback frequencies; the lower panel presents the effect of

Figure 2. Changes in mean (upper panel) and *SD* (lower panel) of the force output with gain. Each “a” and “b” indicates a significant ($p < .05$) difference from 2 p/N and from 32 p/N, respectively. The dashed line on the upper panel marks the average target force of 6.1 N.

Figure 3. Changes in force *SD* (upper panel) and *RMSE* (lower panel) with feedback frequency. Each "a" indicates a significant ($p < .05$) difference from 0.4 Hz.

feedback frequencies of ApEn at the different levels of visual gain.

Visual gain and feedback frequency in the common informational metric of spatial and temporal uncertainty and their relation to ApEn are presented in the upper and lower panels, respectively, of Figure 5. With data from all the participants, quadratic function fits yielded r^2 values of .85 and .90 for the spatial and temporal uncertainty, respectively. Following de Ruyter van Steveninck et al. (1996), a 3-D surface was created to capture the interaction between spatial and temporal uncertainty on ApEn from the sums of the quadratic function fits. The intercept, xy_0 , was obtained from an average of the intercepts of both the fitted functions. The final function for the surface can then be described in terms of spatial (x) and temporal (y) uncertainty:

$$\text{ApEn} = xy_0 - 0.0054x^2 + 0.04x - 0.0063y^2 - 0.01y. \quad (4)$$

The generated response surface is able to explain 69% of the total variance, and is presented in Figure 6.

DISCUSSION

The effects of visual gain and frequency of visual feedback significantly changed the amount and structure of variability in force output. Visual gain significantly affected the mean force produced, whereas feedback frequency significantly affected the magnitude and structure of variability. The central finding is the interaction between visual gain and feedback frequency, which revealed compensatory effects of spatial and temporal uncertainty in the visual display on the informational content (Fitts, 1954; Shannon, 1948) of the force output dynamics.

Feedback Effects on the Distributional Properties of Force Output

Visual gain significantly affected the mean and *SD* of the force generated by the participants. The significantly lower mean force output at 2 p/N, the lowest visual gain, reflects a tendency to undershoot the target when visual feedback is less sensitive to fluctuations in force produced by the finger. As gain increased, participants were able to generate forces that were closer to the target (see Figure 2). Magnitude of variability was significantly higher at lower gain levels—namely, 2 and 32 p/N, in comparison with the highest gain level of 512 p/N. Frequency of the visual feedback, however, had no effect on mean force produced. Magnitude of variability and variable error were both significantly affected by the frequency of visual feedback. At the lowest feedback frequency (2 Hz), *SD* and *RMSE* were significantly higher than were all the other feedback frequencies.

Table 2
p Values Obtained From the Tukey Post Hoc Tests of the Main Effects of Gain and Frequency on ApEn

Gain Level	2 p/N	32 p/N	128 p/N	256 p/N	512 p/N
2 p/N	—	.0631	.0022*	.0057	.9698
32 p/N	.0631	—	.7127	.8853	.0129*
128 p/N	.0022*	.7127	—	.9971	.0004
256 p/N	.0057**	.8853	.9971	—	.0010**
512 p/N	.9698	.0129*	.0004**	.0010**	—
Frequency Level	0.4 Hz	3.2 Hz	12.8 Hz	25.6 Hz	
0.4 Hz	—	.0002**	.0002**	.0002**	
3.2 Hz	.0002**	—	.0203*	.0034**	
12.8 Hz	.0002**	.0203	—	.8962	
25.6 Hz	.0002**	.0034**	.8962	—	

* $p < .05$. ** $p < .01$.

Figure 4. Effects of visual gain on force output complexity (ApEn) separated by levels of frequency (upper panel). Effects of feedback frequency on force output complexity (ApEn) separated by levels of visual gain (lower panel).

What is clear from these findings is that magnitude of variability is reduced with increased feedback precision. As more feedback is presented within a smaller amount of time or space, the magnitude of variability is decreased. The ability to track the target line over time, however, is dependent on feedback frequency, as indexed by the significant effect on RMSE. Such a reduction in errors is in line with previous experiments involving intermittency in visual feedback, where the occurrence of errors is reduced (Assaiante et al., 1989; Elliott et al., 1994; Robertson et al., 1994). With the continuous nature of the task employed in this experiment, it is not the number of discrete errors, but rather, the magnitude of the deviation from the desired force that is reduced with increased feedback frequency (Slifkin et al., 2000). The convergence of these findings shows that, with a greater feedback frequency, participants were more able to make adjustments to deviations from the target line.

Gain, however, affects the participants' ability to approximate the target line and produce the desired mean force, a finding consistent with the effects of KR precision on movement outcome (Newell & Kennedy, 1978; Rogers, 1974). With low gain levels, the participants tended to undershoot the target, because a large undershoot would still be represented, spatially, as being close to the line. Potentially, participants preferentially undershot the target as a means of reducing variability, knowing that the *SD*

of force has been found to grow exponentially with force output in such continuous force production tasks (Slifkin & Newell, 1999).

Another interesting finding is the change in between-participants variability with the feedback manipulations. From Figures 2 and 3, it is clear that there is an accompanying reduction in variability between participants as a function of feedback precision in both the spatial and temporal domains. These findings suggest that individual differences in motor performance are magnified by a reduction in visual feedback precision. This is in line with the study of the effect of visual gain on force output in older adults (Sosnoff & Newell, 2006).

Visual Information and the Dynamic Properties of Force Output

When averaged across the different levels of feedback frequency, the amount of information required to capture the force output dynamics changed as an inverted-U function with increasing levels of gain (Newell & McDonald, 1994; Stephens & Taylor, 1974). Solving for the first derivative of the fitted quadratic function yields a maximum at 218 p/N, where informational content of the force dynamics is at its highest. This finding is similar to

Figure 5. ApEn averaged across levels of temporal uncertainty as a function of spatial uncertainty (upper panel) and averaged across spatial uncertainty as a function of temporal uncertainty (lower panel). The least-squares fitted functions (solid gray lines) and r^2 values are presented in the upper right corner of each panel.

Figure 6. Uncertainty surface obtained from sums of quadratic function fits of ApEn to spatial and temporal uncertainty.

that from Sosnoff and Newell (2006), where the scaling exponent of the detrended fluctuation analysis was at its lowest between visual gain levels of 64 and 256 p/N. The effect of increments in feedback frequency resulted in a nonlinear decrease in the information contained within the force dynamics (see also Slifkin et al., 2000). Detailed inspection of the interaction between gain and frequency (Figure 4) shows that the function of change in ApEn was not similar across the different levels of frequency. At the lowest feedback frequency (4 Hz), increasing visual gain resulted in a decrease in motor information rather than the inverted-U function. With different levels of gain, the general function of change with increasing feedback frequency is maintained, but differences in rate of change across the different gain conditions are apparent.

When the averaged data are converted to the uncertainty metric (Figure 5), one can see that spatial uncertainty possessed an inverted-U relationship between ApEn, whereas increases in temporal uncertainty resulted in decreases in ApEn. When the effects of both uncertainties are combined, through a superposition of quadratic functions, the compensatory nature of the two sources of uncertainty is revealed. With the assumption that both functions converge toward a peak, the averaged intercept and the surface generated by the sum of the quadratic functions provides an explanation of the effects of uncertainty on the force output dynamics (Figure 6). This response surface represents the compensatory effects of spatial and temporal uncertainty on the uncertainty in the motor output, highlighting the mutuality inherent in spatial and temporal information. At the peak of the surface, spatial and temporal uncertainties are at their lowest, and the entropy of the motor output dynamics is at its highest. Entropy of the motor output would be at its lowest when both uncertainties are at their highest. The combined effect of uncertainty in the display occurs across the decreases in motor uncertainty, because high levels of spatial uncertainty are compensated by low levels of temporal uncertainty, and vice versa.

At low levels of uncertainty in the visual feedback display, greater uncertainty in the motor output is afforded.

Greater levels of uncertainty in the visual display must be compensated for through an increase in predictability of the force fluctuations. At the lowest levels of visual display uncertainty, force output uncertainty reaches its peak. It is likely that such a limit to motor uncertainty is present due to musculoskeletal linkages that prevent the fluctuations in human postural tremor from being an entirely random (white noise) process (Newell, Deutsch, Sosnoff, & Mayer-Kress, 2006). At the other extreme of the uncertainty scale, there is a maximum level of uncertainty in the visual feedback that allows for the task goal to be achieved. This is due to an inherent uncertainty in the motor system that cannot be eliminated in its entirety (van Beers, Baraduc, & Wolpert, 2002). As such, a minimum amount of visual or haptic information from the environment would be requisite for the guidance of motor tasks. The most important finding, however, is that spatial information is able to compensate for a lack of temporal information, and vice versa, an effect similar to the effect of velocity and contrast on the blowfly neuron (de Ruyter van Steveninck et al., 1996). Thus, situations in which the precision of visual feedback in spatial terms is minimal, presenting a greater amount of information within a shorter time window, and vice versa, may serve to reduce the uncertainty within the environment.

A lack of perfect symmetry of the response surface for spatial and temporal uncertainty, however, points to the problem that both uncertainties are not directly equivalent. Although this study has extended the findings of Sosnoff and Newell (2006) by accounting for the size of the display as a means of estimating spatial entropy, temporal uncertainty can at best be approximated using assumptions based on physiological data. Potentially, the use of eye-tracking technologies will aid in the understanding of the temporal properties in the acquisition of visual information. Another possibility is that spatial and temporal properties of visual information are encoded differently than they are in the blowfly, due to the more complex structure of the human brain. Future research should continue to seek a common metric for the estimation of uncertainty in the visual information obtained from the environment in the manual control of force output.

AUTHOR NOTE

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