Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/terg20

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Available online: 22 Nov 2011

Ergonomics
Vol. 54, No. 12, December 2011, 1159–1174

Factors affecting numerical typing performance of young adults in a hear-and-type task

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(*Received 2 March 2010; final version received 8 September 2011*)

Numerical hear-and-type tasks, i.e. making immediate keypresses according to verbally presented numbers, possess both practical and theoretical importance but received relatively little attention. Effects of speech rates (500-ms vs. 1000-ms interval), urgency (urgent condition: performance-based monetary incentive plus time limit vs. non-urgent condition: flat-rate compensation) and finger strategies (single vs. multi-finger typing) on typing speed and accuracy were investigated. Fast speech rate and multi-finger typing produced more errors and slower typing speed. Urgency improved typing speed but decreased accuracy. Errors were almost doubled under urgent condition, while urgency effect on speed was similar to that of speech rate. Examination of error patterns did not fully support Salthouse's (1986) speculations about error-making mechanisms. The results implied that urgency could play a more important role in error-making than task demands. Numerical keyboard design and error detection could benefit from spatial incidence of errors found in this study.

Statement of Relevance: This study revealed that classic speculations about error-making mechanisms in alphabetical typing do not necessarily translate to numerical typing. Factors other than external task demands such as urgency can affect typing performance to a similar or greater extent. Investigations of intrinsic error-making factors in non-traditional typing tasks are encouraged.

Keywords: numerical typing; errors; multi-tasking; serial reaction time; speed–accuracy trade-off

1. Introduction

Numerical typing is an error-prone, often daily task important to understanding human performance in skilled, perceptual–motor activities. Numerical typing errors can cause serious consequences in critical systems, such as medical databases or nuclear power plants. In a pioneering study, Gough *et al.* (1983) found that inaccurate recording of data caused by numerical typing errors was one of the greatest problems in establishing a surgical data system. A quantitative evaluation by Arndt *et al.* (1994) discovered that 2.4% of the received data from seven medical centres were incorrect. Although this percentage may seem to be small, the hidden risk can be huge. Patients could actually die due to number entry errors in a popular drug delivery system utilised by the hospitals (Thimbleby and Cairns 2010). Numerical typing errors also contributed to input errors in control of nuclear power plants to such an extent that incremental input devices were suggested as an alternative interface to numerical keyboards (O'Hara *et al.* 2008). Other alternative data entry devices, such as automatic speech recognition, may be used to avoid manual typing, but they may not have any advantages in error rates and data entry speeds when they are compared with standard numerical keyboards for numerical data entry (Szeto *et al.* 2005).

Beside the menace to lives, numerical typing errors could cause financial loss in transactional systems and have been thought to be more problematic than frauds (Bohm *et al.* 2008). These problems are exacerbated by the fact that numerical typing errors are hard to detect. Kawado *et al.* (2003) investigated error detection rates for two data verification methods by human operators, and only 45.5–68.2% of numerical errors were detected. The results implied that half of the errors may remain undetected and, thus, uncorrected. A recent study by Thimbleby and Cairns (2010) also indicated that a safety-critical device may neither block predictable errors nor give the user an opportunity to correct errors. Since error detection and its resultant corrections afterwards may not be reliable, it would be better to investigate why people make numerical typing errors in the first place.

1.1. *The hear-and-type task*

Hear-and-type tasks, i.e. making immediate keypresses consecutively according to auditory signals presented, are of particular research interest due to their

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ISSN 0014-0139 print/ISSN 1366-5847 online

http://dx.doi.org/10.1080/00140139.2011.622794
http://www.tandfonline.com

prevalence and vulnerability to errors, yet have received little attention. In daily life, numbers are often typed based on verbal information. People routinely enter contact numbers of their friends into cell phones through conversation. Service agents input tracking numbers into computers when talking with customers by phone. In these cases, they type numbers instantly following auditory stimuli. Unlike transcription typing, the hear-and-type task is a force-paced task in which typists react rapidly to transient stimuli without preview. In transcription typing, skilled typists can make use of permanent visual presentation to create a running buffer of encoded stimuli (preview) for parallel processing. Therefore, they can self-pace typing without feeling much time pressure imposed by feeding of information. In contrast, typists often need to immediately transcribe what they heard without buffering in hear-and-type tasks, because the pace is regulated by the inter-stimuli interval (ISI) of auditory information. In this situation, short ISI can produce temporal overlaps between processings of consecutive stimuli and result in multi-tasking (Wickens and Hollands 1999). The multi-tasking may impinge on speed and accuracy of numerical typing if the ongoing typing interferes with the processing of subsequent stimuli. The vulnerability of hear-and-type tasks becomes even more salient in numerical context. If a typist performs an alphabetical typing task, s/he can easily identify a wrongly typed word such as 'DOK' or 'CAK'. This top-down error detection mechanism is not available in numerical typing. Re-check is also limited due to the transient nature of the original copy, i.e. the auditory stimuli.

Distinctions between alphabetical transcription typing and hear-and-type tasks, coupled with emphasis on memory aspects of numerical typing in the literature, necessitate an experimental study to disclose error-making mechanisms. Many studies have been done in the field of alphabetical transcription typing, and Salthouse (1986) summarised major findings on error-making mechanisms. According to his summary, different types of errors were accompanied by unique behavioural patterns from which sources of errors could be inferred. Whether those observations would hold true in numerical typing, however, needs further examination. Previous studies in numerical typing have focused on the role of working memory in memorise-and-type tasks, i.e. memorising numbers and then typing recalled numbers in a later time (Nordby *et al.* 2002, Raanaas *et al.* 2002, Farrell and Lewandowsky 2004). The limited capacity of working memory may contribute to typing errors in memorise-and-type tasks, but, in hear-and-type tasks, typists often transcribe immediately what they heard. Since the latency between the stimuli and the responses is typically within 1 s, rehearsal may not be available to maintain auditory information in working memory (Logie 1996, Galotti 2004). Without maintaining memory trace, typists can still type in the meantime but do not necessarily recall what they heard at a later time. Untimely evaluation of stimuli, inappropriate motor program formulation for responses or imprecise execution of typing should therefore play more important roles than memory failure in making errors (Salthouse 1986). Factors associated with timing, response selection and motor execution were, therefore, considered in the current study instead of factors relevant to memory.

1.2. Theoretical frameworks

The nature of numerical hear-and-type tasks is a combination of choice reactions and rapid aiming tasks realised in a serial reaction time (RT) paradigm. When there are auditory stimuli presented, attended auditory features are firstly recognised as meaningful digits. Appropriate motor responses, e.g. using index finger to press '1' key, are then selected accordingly as choice reactions. The designated body parts (including fingers, the wrist and the arm) must be shifted quickly and accurately from an initial position to another desired terminal position in these reactions. The movements which must terminate within a specified target region are, therefore, spatially constrained while attempting to minimise movement time, resulting in rapid aiming. The response selections and executions are performed continuously with possible temporal overlaps, depending on pacing. The consecutive typing movements, therefore, form a series of reactions.

In a force-paced, serial RT paradigm, pacing, response complexity and processing demands can influence speed and accuracy (Wickens and Hollands 1999, Van Galen and Van Huygevoort 2000). In the case of fast pacing and short ISI, the execution of aiming movements may be handled simultaneously with another auditory recognition, resulting in temporary multi-tasking. Multiple resources model predicts that the ongoing manual task and the interfering verbal recognition task can be handled simultaneously if they are carried out in different modalities (Wickens 2002). Evidence also showed that skilled typists can process verbal tasks well in parallel while doing alphabetical transcription typing (Salthouse 1986). However, competition of resources can eliminate inter-modality benefits if attention is needed to maintain the execution of the ongoing task (Wickens *et al.* 2005). In hear-and-type tasks, uncertainty about keys to be pressed increased the attentional demand in numerical typing tasks

(Hutton and Tegally 2005). Although predictability of frequent stimuli can diminish attentional demand, high response complexity that requires more monitoring and demands intense processing would also affect effectiveness in parallel processing (Wickens and Liu 1988, Wickens and Hollands 1999). The effectiveness of multi-tasking in numerical hear-and-type tasks, therefore, needed to be investigated under different pacing and response complexity.

The processing demands can be further intensified by typists' internalised urgency towards the situation. The urgency is regarded as an intrinsic motivation to finish the work quickly with a certain level of accuracy so that a tangible reward (e.g. money) can be obtained. Tangible rewards contingent to the quality of the work can increase the intrinsic motivation (Eisenberger and Cameron 1996). Neuroscience research demonstrated that monetary rewards activated a cerebral area specific to the contextual value of the task but independent of the levels of task difficulty (Pochon *et al*. 2002, Williams *et al*. 2004). Based on these findings, we expected urgency pertaining to tangible rewards would increase time pressure in addition to extrinsic demands, such as pacing and response complexity. Although time pressure has been studied extensively for its effects on speed–accuracy trade-off (SATO) in RT paradigms, Van Galen and Van Huygevoort (2000) argued that systematic efforts have not been made to analyse the effects of speeded RT on the quality of movement and on spatial error, especially in combinations of time pressure with other psychological stresses, like dual task load (Van Galen and Van Huygevoort 2000). Therefore, urgency should be considered as another dimension of job strain that affects processing demand (Bakker and Demerouti 2007) and possesses potential impacts on automaticity in hear-and-type tasks.

1.3. Goals and hypotheses

The current study investigated the effects of factors associated with pacing, response complexity and the extent of processing demand on numerical typing performance of young adults. The speech rate of auditory stimuli was used as a pacing factor. Different finger strategies, i.e. typing by a single finger or multiple fingers, were manipulated as different levels of response complexity. Multi-finger typing is vulnerable to error due to its complicated motor programming of finger assignments and greater stimulus–response (S–R) numerosity, i.e. more S–R pairs to select from. It is also subject to a well-known finger-enslaving effect: undesired force is produced by fingers that are not instructed to produce force when the required force exceeds 2.5% of maximal voluntary contraction generated by the target finger (Kilbreath and Gandevia 1994). A common method to intensify processing demands is to provide performance-based rewards contingent to work performance. Therefore, monetary rewards based on typing performance were also manipulated to see if urgency, in addition to and independent of pacing, would further affect numerical typing performance. Performance under fast speech rate was expected to be both slower and less accurate due to multi-tasking. The multi-finger typing was also hypothesised to be detrimental to both typing speed and accuracy. Urgent condition related to higher intrinsic motivation, however, was expected to have shorter RT but more errors due to SATO. Finally, as in Salthouse's review (Salthouse 1986), error phenomena were subject to a behavioural pattern analysis in an attempt to verify if error-making phenomena observed in alphabetical typing would translate to numerical typing.

2. Method

2.1. Experimental variables

Speech rates, urgency levels and finger strategies were manipulated in the experiment. The speech rate was defined by ISIs. Random nine-digit numbers (to be typed) were read out by a computer program digit-by-digit, not linguistically chunked, i.e. '123' was read as 'one-two-three' instead of 'one hundred twenty-three'. The inter-digit intervals were 500 and 1000 ms for fast and slow speech rate, respectively (Raanaas *et al*. 2002). Furthermore, there was a 300-ms pause between every three digits because, based on participants' feedback from authors' pilot study, this was the most natural way to read out numbers without any specific format known beforehand. The structure of the random nine-digit number is shown in Figure 1.

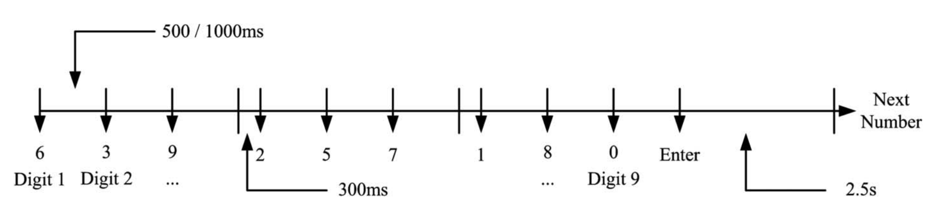

Figure 1. The structure of the nine-digit number.

Urgency was manipulated by two different compensational polices: a flat-rate payment and a performance-based reward. In non-urgent condition, the participants receive a flat-rate payment independent of her/his performance. In urgent condition, the participant's reward was contingent upon her/his performance in both accuracy and speed. Only correct responses within 600 ms counted as 'passes'. Under urgent condition, a successful participant could obtain four times the money that s/he could get in non-urgent trials. Participants were also instructed to use two different typing strategies: single finger and multi-finger typing. For single finger typing, participants used only their right index fingers. For multi-finger typing, a recommended multi-finger pattern (Figure 2) was given to participants.

The experiment was a within-subject design, in which each participant must complete all eight trials of two speech rates, two urgency levels and two finger strategies. During each trial, RT to each digit and errors were recorded. The RT was defined as the lapse between the presentation of the auditory stimulus and the depression of the key. When a single keypress did not match the corresponding digit presented, an additional depression was made, or an auditory stimulus did not receive a response, an error had occurred. Dependent variables used in statistical analysis consisted of the mean RT of correct responses and the number of errors in each trial, as well as the passing rate of responses in urgent trials.

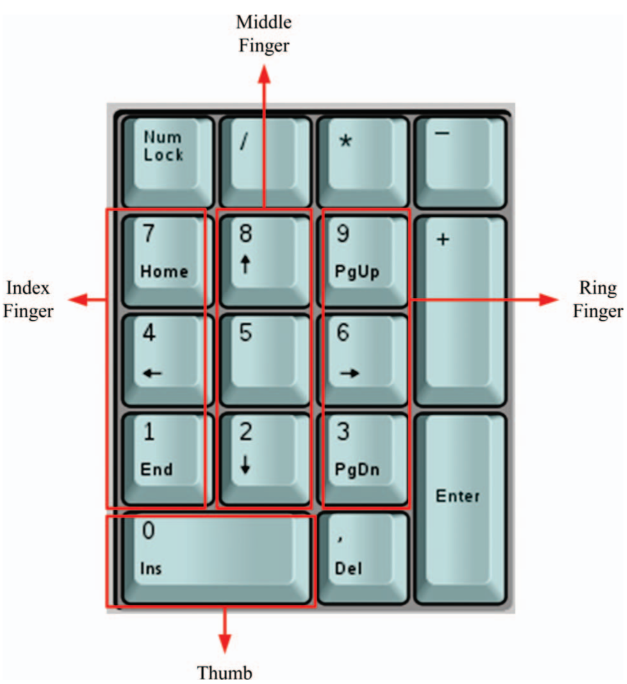

Figure 2. Recommended multi-finger pattern.

2.2. Participants

Twenty participants were recruited from the college community in this study, including 13 males and 7 females (average age: 22.6 years old). They were all young, native speakers of English without any hearing disability. The participant group was considered representative of a youthful working force (Bureau of Labor Statistics 2010) with intact perceptual–motor abilities. A numerical typing pretest was required before participation to ensure their familiarity with numerical typing. They were instructed to type out 30, random, nine-digit numbers using both a single finger and multi-fingers within 200 s, with at least 80% accuracy in terms of digits. This requirement is above the mean performance of participants in a previous numerical typing study (Marteniuk *et al.* 1996) and comparable to representative number keying rates of skilled typists (Seibel 1977). All participants signed informed consent before the experiment, and they were compensated for their time of participation (flat-rate compensation). Their typing performance in pretest is listed in Table 1. A simple two-sample *t* test showed that there was no gender difference in terms of typing speed or accuracy in pretest.

2.3. Experimental task and procedure

The experiment was comprised of eight trials of typical hear-and-type tasks which emulated daily work in banks or customer service. In each trial, a computer program read out 30 random numbers of nine digits in either fast or slow speech rate, and participants were told to type out those numbers on a standard numerical keyboard (Figure 3). Each random number was followed by a 2.5-s pause during which participants were reminded to press 'enter'. Before each trial, participants were also told which finger strategy should be used and whether this is an urgent trial. In urgent trials, participants were informed that a performance-based reward would apply; so, they should type both accurately and quickly to obtain as much bonus as possible. To further assure that participants experienced urgency, a warning signal 'Too late!' would appear whenever participants' RT exceeded 600 ms. This emulates what bank tellers or customer service agents might experience in a competitive work environment if they are stressed by

Table 1. Typing performance of participants in pretest.

Gender	Male	Female
Age	22.9	21.9
Pretest speed (keys/min)	101.5	98.5
Pretest accuracy (% of correct keystrokes)	92.0	93.1

Figure 3. A standard numerical keyboard.

the task or customers while pursuing high performance pertaining to monetary reward. In contrast, participants were asked to maintain high accuracy in non-urgent trials, where quick responses were not necessary as long as they could catch up with the speech rate. This corresponds to the situation when the task is not urgent and bank tellers or customer service agents can type every digit as correctly as possible.

At the beginning of the experiment, all participants were pretested on her/his typing skill as mentioned in Section 2.2. Participants were allowed to adjust the volume and other settings of the typing environment to their preference. The settings were maintained the same throughout the whole experiment. Two practice trials of fast speech rate and urgent condition combined were given prior to formal experimental trials, representing the most difficult levels among all trials. Participants were supposed to perform one practice trial by a single finger and the other practice trial by multi-fingers. Then, they were asked to perform eight trials of aforementioned experimental tasks consisting of two levels of speech rates, finger strategies and urgency. During each trial, participants were video-monitored to assure that they were typing as instructed, and their performance in speed and accuracy was recorded by the computer program for later analysis. The run order of eight trials was random, and a short, 5-min break was given after four trials so that the participants' performance would not be hampered by fatigue. After each trial, a NASA-TLX questionnaire (NASA 2011) and a fatigue-level questionnaire were given to the participants to report their workload as well as subjective fatigue and discomfort. The NASA-TLX questionnaire was used as a tool to detect the effect of urgency in different subjective dimensions. The fatigue questionnaire was used to assure participants' performance was not compromised, since physical discomfort and fatigue were found to have adverse effects on typing performance (Liao and Drury 2000).

2.4. *Statistical analysis*

Behavioural data were examined by analysis of covariance (ANCOVA) first to confirm whether the expertise of typing shown in the pretest would have any influence on RT or accuracy in the formal test. The typing speed recorded in the pretest was, therefore, regarded as a covariate in the initial statistical model for RT, and the accuracy was considered in the model for errors. The experiment was a $2 \times 2 \times 2$ factorial, within-subject design. Speech rates, finger strategies and urgency levels were the three main factors considered in the statistical model. The total number of errors and the average RT of correct responses in each trial were the two main dependent variables. In addition, the passing rate (the ratio of keystrokes with RT < 600 ms relative to total number of keystrokes) was evaluated by a 2×2 factorial model containing speech rates and finger strategies only. General linear models were assumed for the effects of speech rates, finger strategies and urgency levels. Data were firstly analysed by a full $2 \times 2 \times 2$ model (for RT and errors) or a 2×2 model (for passing rate) to see if there were significant covariates or interactions. Then, the initial model was reduced to contain only the significant covariate, main effects and interactions. Finally, the resultant ANCOVA models along with their fitness were reported. To further assure control of fatigue and support main findings based on behavioural data, subjective ratings in the NASA-TLX and the fatigue questionnaire were also analysed to facilitate interpretation of statistical results.

2.5. *Examination of error patterns*

To confirm error-making mechanisms suggested by Salthouse (1986), participants' behavioural patterns specific to erroneous keystrokes were analysed based on the spatial incidence and compositions of error types and then compared to reaching difficulty. Typing errors were firstly categorised into substitution ('113' for '123'), intrusion ('1123' for '123'), omission ('13' for '123') and transposition ('132' for '123') errors. The incidence of each type of error was then illustrated by the ratio of erroneous keystrokes in different locations on a numerical keyboard. The RT of correct responses stratified by keys (0–9) was also graphed spatially on a numerical keyboard (spatial distribution) as indicative of the reaching difficulty. By checking conformity of the spatial incidence of errors to the spatial distribution of RT, association between errors and reaching difficulty could be confirmed. Comparing composition of errors between factorial pairs, i.e. fast vs. slow speech rate, single vs. multi-finger and urgent vs. non-urgent trials, could also reveal the effects of experimental factors on particular type of errors. The outcomes would be reported using compare-and-contrast with Salthouse's findings.

3. Results

3.1. *Errors of numerical typing*

All the three main factors (speech rate, finger strategy and urgency) were found to significantly affect the total number of errors committed in a trial. Also, accuracy in pretest was found to be a significant covariate in ANCOVA model. No interaction was found significant in the full model; therefore, they were all excluded in the final model. The result of the reduced ANCOVA model is shown in Table 2. The effects of main factors are plotted in Figure 4. Fast speech rate, multi-finger typing and urgent trials resulted in more errors. The effect of urgency is relatively high, and the number of errors almost doubled in urgent condition (6 → 11).

3.2. *RT of numerical typing*

In the full ANCOVA model, no covariate or interaction was found to be significant; therefore, they were all excluded. The reduced model included only three main factors that had significant effects on RT in numerical typing. The ANCOVA is shown in Table 3, with effect plots of the three main factors shown in Figure 5. Based on the plots, the RT is the shortest when the trial was urgent, and the more complex multi-finger strategy resulted in longer RT as expected. Fast speech rate caused longer RT, implying that delay could occur due to pacing factor alone regardless of response complexity and urgency level.

3.3. *Passing rate of numerical typing*

Finger strategies were found to significantly affect the passing rate ($F_{1,58} = 4.26$, p value < 0.05, $R^2 = 89.84\%$), while other covariates, main factors and interactions were not significant. Single finger typing had significantly higher passing rate than multi-finger typing.

Table 2. ANCOVA for errors.

Factor	Effect (frequency)	F value	p value	R^2
Pretest accuracy[1]	–	$F_{1,136} = 5.12$	0.025*	57.12%
Speech rate	0.875	$F_{1,136} = 6.31$	0.013*	
Finger strategy	0.775	$F_{1,136} = 6.32$	0.013*	
Urgency	2.338	$F_{1,136} = 45.05$	<0.001**	

Notes: [1]Covariate; *$p < 0.05$; **$p < 0.01$.

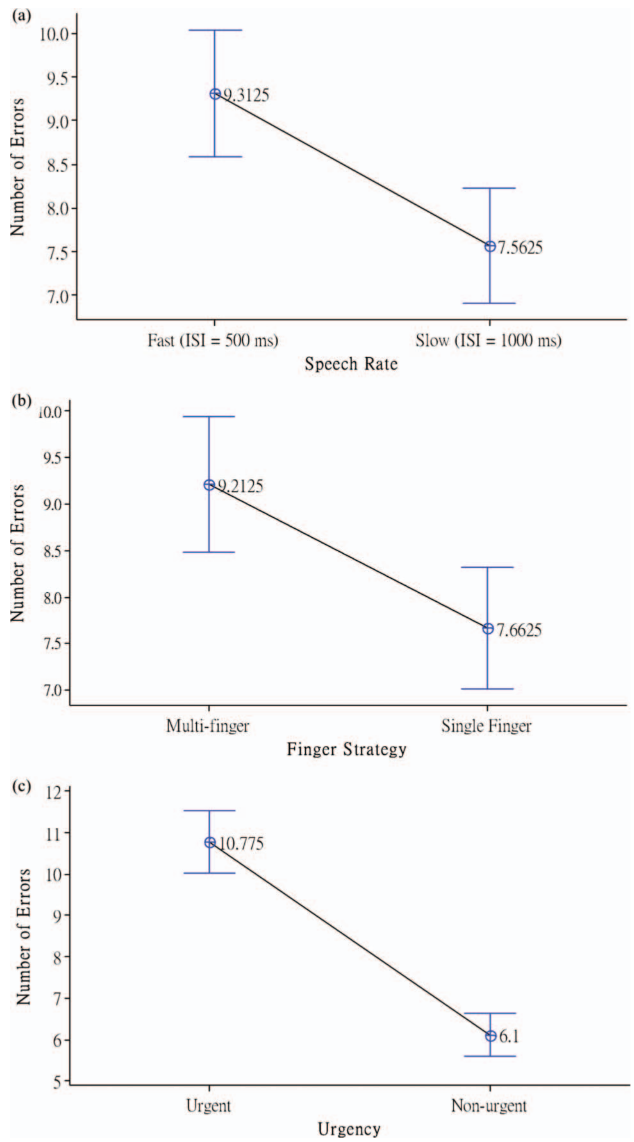

Figure 4. Effects of speech rates, finger strategies and urgency on errors. (Bars are one standard error from the mean.)

Table 3. ANCOVA for RT.

Factor	Effect (ms)	F value	p value	R^2
Speech rate	19	$F_{1,137} = 21.37$	<0.001**	
Finger strategy	11	$F_{1,137} = 7.09$	0.009**	68.46%
Urgency	22	$F_{1,137} = 28.69$	<0.001**	

Note: *$p < 0.05$; **$p < 0.01$.

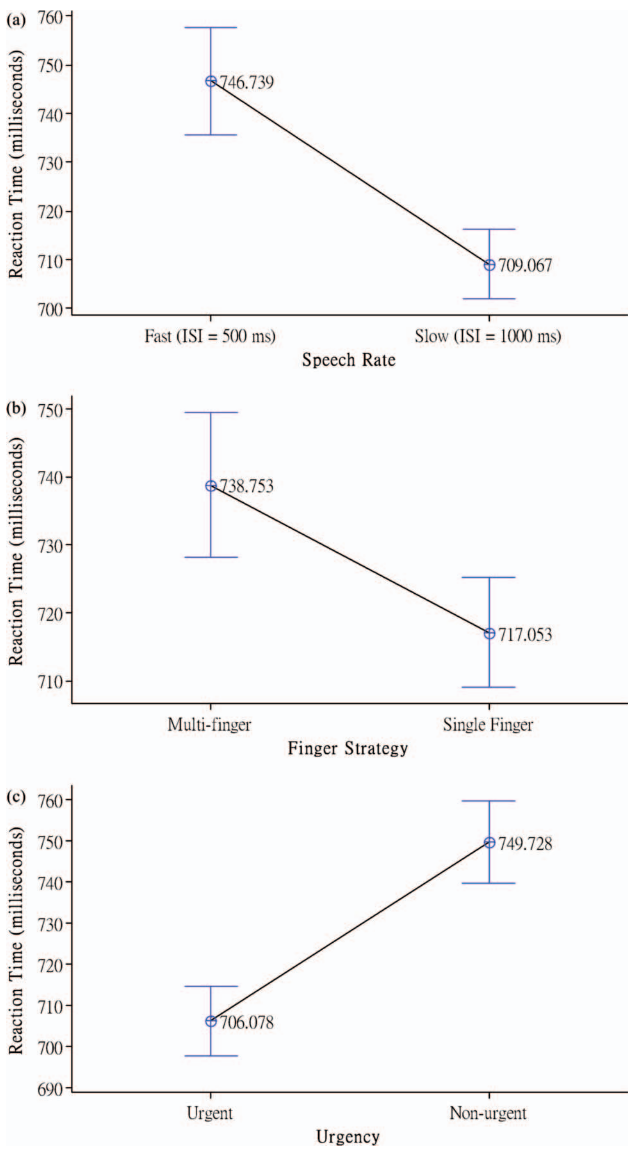

Figure 5. Effects of speech rates, finger strategies and urgency on RT. (Bars are one standard error from the mean.)

3.4. *Error patterns in numerical typing vs. alphabetical tying*

Figure 6 illustrates the composition of error types in numerical typing. In general, substitution and intrusion errors constituted 90% of errors. It was proved

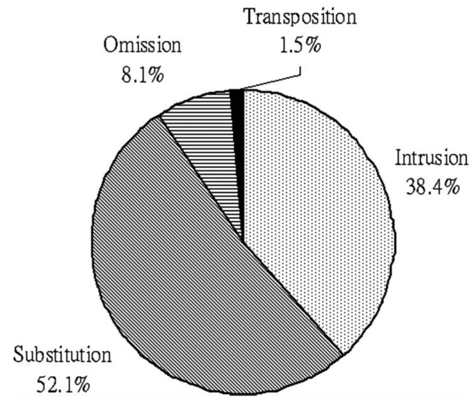

Figure 6. Composition of error types.

true that substitution errors involved adjacent keys (76.9% of substitution errors involved adjacent keys: 33.9% horizontal and 43.0% vertical), but, in numerical typing, this is attributable to proximity of all keys on the numerical keyboard. The assumption that substitution errors were caused by faulty assignments of movement specifications at the finger level was disproved by comparison between single and multi-finger typing (49.6% in single finger typing vs. 50.4% in multi-finger typing, Figure 7). Also, rarely was the previous key pressed repeatedly as a substitute for the current key (8.13%). The substitution errors in numerical typing tended to happen under urgent trials: 64% vs. 36% in non-urgent trials (Figure 7). Similarly, intrusion errors were affected most by urgency (65% in urgent trials vs. 35% in non-urgent trials, Figure 8), while finger strategies and speech rates had minimal influence. A relatively high percentage (15%) of previous keys was repeated during intrusion errors, compatible with Salthouse's speculation (Salthouse 1986).

Omission and transposition errors were scarce (less than 10%, Figure 6). The spatial incidence of omission errors is shown in Figure 9 with the average RT of correct keystrokes. Unlike what was suggested by Salthouse (1986), omission errors did not involve keys that are difficult to reach: the spatial incidence of omission errors (Figure 9c) did not correspond to the keys with longer RT (Figure 9d). Keys with higher force criterion to be pressed, however, indeed had a relatively higher chance of becoming omission errors, as with the '0' key. Noticeably, omissions of the '0' key appeared mostly in multi-finger typing (see Appendix 1, omission column in Figure A-1). This implies that the reaching difficulty may be attributable to the thumb's lower depression force in multi-finger typing due to the finger-enslaving effect (Jones and Lederman 2006).

Based on the error mechanisms suggested by Salthouse, transposition errors should be absent due to the lack of alternation of two hands, and this was

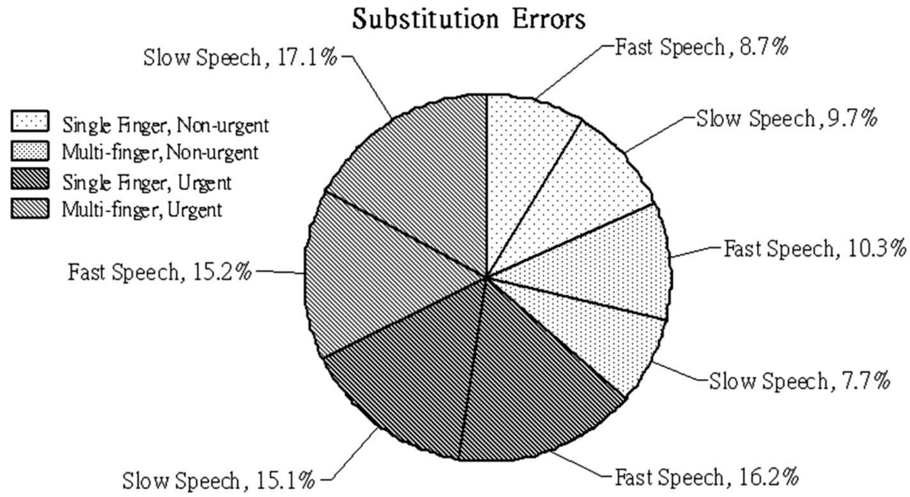

Figure 7. Composition of substitution errors.

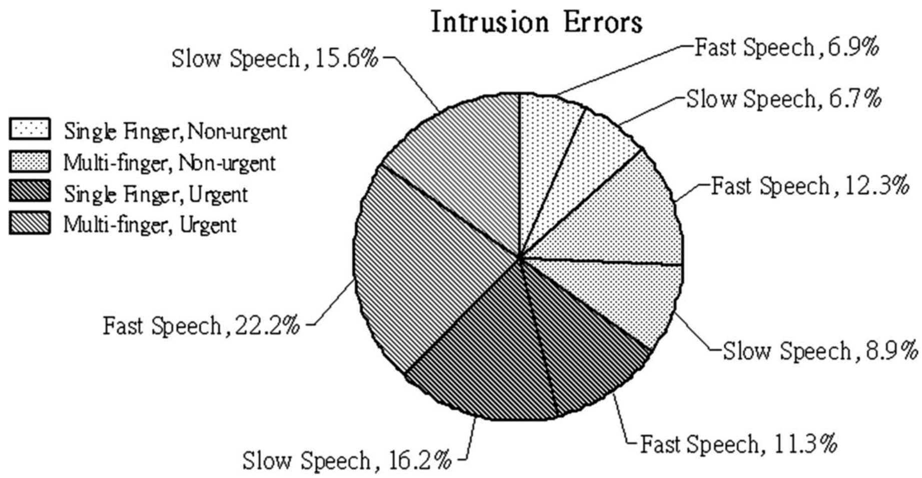

Figure 8. Composition of intrusion errors.

confirmed in the current study. Transposition errors were extremely rare (only 10 transpositions happened in more than 48,000 keypresses) and happened exclusively in trials of fast speech rate (ISI = 500 ms). As suggested by Salthouse, transposition errors were caused by alternation of two hands in alphabetical typing, but, in numerical typing, transposition errors seemed to involve inefficacy of multi-tasking. In summary, the findings confirmed some error phenomena suggested by Salthouse (1986). However, different error patterns also emerged, implying that error mechanisms in alphabetical typing do not necessarily translate to numerical typing (Table 4).

3.5. *Effects of urgency on subjective ratings and fatigue*

The results from statistical analysis of behavioural data and examination of error patterns revealed the important role of urgency in making errors. The effect of urgency was also reflected in subjective ratings for temporal and mental demand on the NASA-TLX questionnaire. Tukey's pair comparison showed that urgency caused a significantly higher rating in temporal demand during multi-finger typing regardless of speech rates (Table 5). Urgency also caused significantly high mental demand under slow speech rate regardless of finger strategies (Table 6). Effect of urgency was not significant in other dimensions except to cause higher frustration in fast speed, multi-finger typing (p value = 0.022). In general, urgency caused higher temporal demand in multi-finger typing and had a significant effect on mental demand when speech rate was slow. To assure participants' fatigue was controlled, the subjective ratings of fatigue were also analysed. During the experiment, participants reported medium fatigue level which increased slightly over time. The difference in fatigue between the beginning

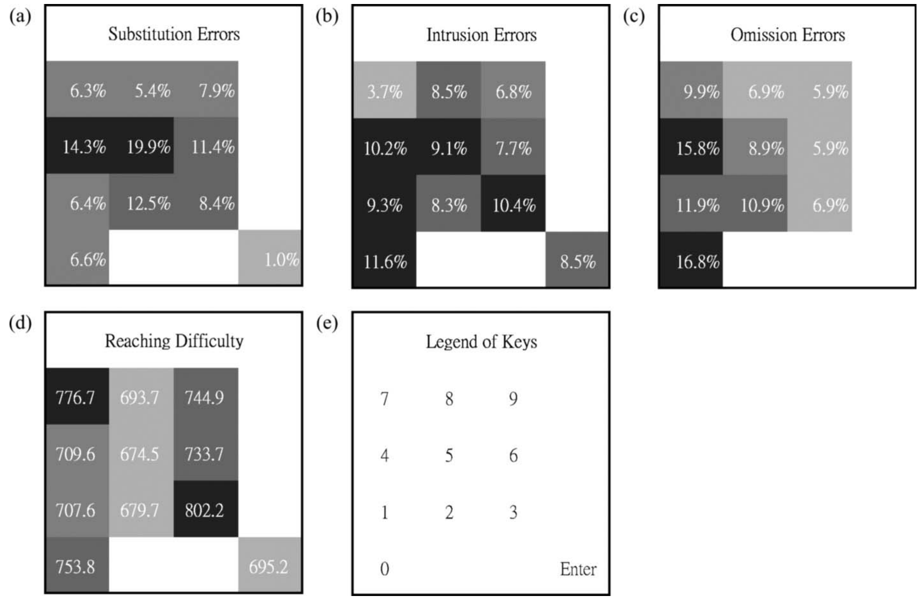

Figure 9. Spatial incidence of substitution, intrusion, omission errors and reaching difficulties of different keys. (For spatial incidence, the gray scale represents relative concentration of errors; the darker the colour, the higher the concentration. The values on keys for reaching difficulty plot are RT in seconds; the gray scale represents relative difficulty in reaching the key; the darker the colour, the more difficult to reach the key.)

Table 4. Comparison of error-making phenomena in alphabetical typing and numerical typing.

	Salthouse (1986)	Current study
Speculations about error-making mechanisms	1. Many substitution errors involved adjacent keys and were caused by faulty assignments of the finger movements.	1. 76.9% of substitution errors involved adjacent keys but it was partially caused by proximity of all keys on the numerical keyboard. Multi-finger typing did not significantly increase substitution errors.
	2. Many intrusion errors involved repeated depressions of previous keys.	2. 15% of previous keys were repeated during intrusion errors, compatible to Salthouse's speculation
	3. Many omission errors involved keys that are difficult to reach and keys with higher force criterion to be pressed.	3. Omission errors did not involve keys that are difficult to reach, but the '0' key which needed higher depression force had a relatively higher chance of becoming omission errors.
	4. Most transposition errors are cross-hand rather than within-hand due to early reach of the second letter, and, thus, they would be scarce in numerical typing task by one hand.	4. Transposition error only occupied 1.48% of total errors and only 10 transpositions happened in more than 48,000 keypresses. The exclusive occurrence of transposition errors under fast speech indicated their association with multi-tasking.

Table 5. Effect of urgency on temporal demand.

Tukey's pair			*p* value
Fast speech, single finger, urgent	vs.	Non-urgent	0.282
Fast speech, multi-finger, urgent	vs.	Non-urgent	0.027*
Slow speech, single finger, urgent	vs.	Non-urgent	0.115
Slow speech, multi-finger, urgent	vs.	Non-urgent	0.037*

Note: *$p < 0.05$.

and end of the experiment was not significant; so, it was speculated that fatigue did not influence participants' performance dramatically (Figure 10).

4. Discussion

The present study revealed that fast pacing due to high speech rate and greater response complexity in multi-finger typing were detrimental to both RT and accuracy in numerical hear-and-type tasks. The urgency factor, in contrast, induced SATO regardless

Table 6. Effect of urgency on mental demand.

Tukey's pair			*p* value
Fast speech, single finger, urgent	vs.	Non-urgent	0.759
Fast speech, multi-finger, urgent	vs.	Non-urgent	0.125
Slow speech, single finger, urgent	vs.	Non-urgent	0.005**
Slow speech, multi-finger, urgent	vs.	Non-urgent	0.035*

Note: $*p < 0.05$; $*p < 0.01$.

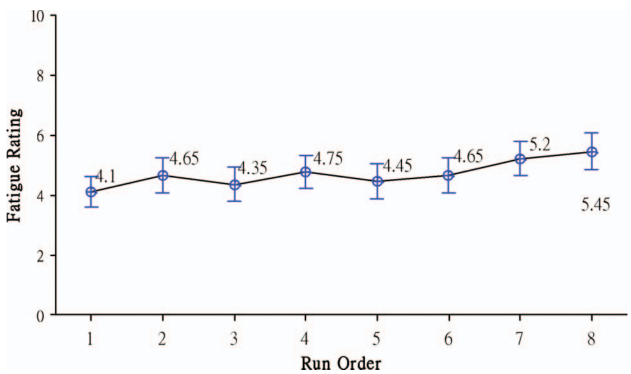

Figure 10. Average fatigue level. (Bars are one standard error from the mean.)

of speech rates and finger strategies; interactions between extrinsic demands (pacing and response complexity) and internalised urgency were not found. A recent study found similar results that mental workload due to multi-tasking decreased typing speed while time pressure imposed by auditory cues increased typing speed at the expense of more errors (Hughes *et al.* 2007). However, the increase of typing errors due to mental workload was not found in that study. Furthermore, examination of error patterns revealed that error mechanisms in alphabetical typing do not necessarily translate to numerical typing. Implications of these findings are discussed in the following along with their applications.

4.1. Speech rates

The disadvantage of fast speech rate is somewhat counter-intuitive. Fast pacing was supposed to be incentive to response time, given that multi-tasking of concurrent manual responses and verbal recognitions was effective. However, fast speech rate (short ISI) caused longer RT and more errors because short ISI created multi-tasking condition, which delayed numerical typing and imposed higher mental workload. Therefore, a bottleneck must have happened at the response-selection stage (Schumacher *et al.* 1999) and caused a temporal delay in processing subsequent stimulus.[1] This bottleneck mechanism has been implemented in Queueing Network-Model Human Processor (QN-MHP) model which successfully modelled basic psychological refractory period (PRP) effect (Wu and Liu 2008).

The manifestation of the temporal delay and typing errors may arise from competition of resources, such as attentional resources or visual guidance. Wickens *et al.* (2005) found that both performance and accuracy of an ongoing visual tracking task were negatively affected by the presentation of auditory information because auditory pre-emption demanded and captured attention (Wickens *et al.* 2005). This explains why both speed and accuracy were degraded in the current study using auditory materials, but only speed was influenced in Hughes *et al.* (2007) using visual materials. Experimental evidence also showed that rapid aiming could use visual guidance to improve accuracy (Smiley-Oyen 1996, Elliott *et al.* 2001), and people became more dependent on the visual guidance as their practice increased (Proteau *et al.* 1992). Since visual guidance is a limited resource that cannot be shared, response selection of the subsequent task might be inhibited during the rapid aiming because the execution of the task would trigger saccadic eye-movements to obtain target information and negatively affect the ongoing aiming task (Godijn and Theeuwes 2002).

It was generally found that experienced typists worked at a near optimal compromise between speed and accuracy if they were self-paced; machine pacing should not be used to manipulate incentives (Seibel 1977, Gerard *et al.* 2002, Hughes *et al.* 2007). This observation is supported by the current finding that fast pacing produced detrimental effects to both speed and accuracy. Gerard *et al.* (2002) also found a sharp increase in subjective discomfort when the typing speed was forced to increase beyond a certain threshold between the typists' self-selected pace and their maximal typing speed. Those findings suggest that forced pacing may result in significant short-term discomfort with minimal improvement, even degradation, in productivity.

4.2. Finger strategies

The finger strategy is related to response complexity or, to be specific, S–R numerosity. Multi-finger typing required matching five (fingers) to 11 (keys), more complex than matching one (finger) to 11 (keys) in single finger typing. Additional delays caused by greater numerosity in RT observed in this study were compatible with additive effects found in PRP studies (Schumacher *et al.* 1999). Furthermore, while traditional PRP study found interaction between pacing and S–R numerosity, in the current study, multi-finger typing caused more errors regardless of speech rate. Lack of interaction could be partly attributed to finger-enslaving effects, i.e. failure to cancel finger-enslaving effects in multi-finger typing might contribute evenly to trials of fast and slow speech rate. This is manifest in the high incidence of omission errors for the '0' key in multi-finger typing (Figure A-1), and no significant difference in the spatial incidence of omission errors between fast and slow speech rate (Figure A-2). Finally, the uncertainty about keys to be pressed might have increased the attentional demand of executing multi-finger typing in hear-and-type tasks (Hutton and Tegally 2005). A common belief that multi-finger strategy facilitates typing performance should take characteristics of various typing tasks into consideration, and single finger typing could be a better choice when there is uncertainty about typing.

4.3. Urgency

The current study revealed that internalised urgency caused by tangible reward pertinent to typing performance could impose as much effect as pacing on RT (Table 3) and more than two times the effect that pacing had on errors (Table 2). Eliminating urgency in working environments, therefore, can be an effective way to reduce typing errors. There was also a clear SATO where RT was improved at the expense of increasing errors, while pacing and response complexity factor degraded both accuracy and RT. When transient stimuli in working memory need to be processed as soon as possible, slow responses might impose greater stress and, thus, also become error-prone (Wickens *et al.* 1984, Wickens and Hollands 1999). In contrast, typists could be induced to exchange accuracy for speed by means of instructions, payoffs, deadline settings or some combination of these techniques (Wickelgren 1977). Although monetary rewards were used to assure participants' maximum effort in improving speed in the current study, accuracy was not deemphasised: participants were instructed to and must react both quickly and accurately to obtain more rewards. Inaccurate but quick responses did not count. Instructions that laid equal emphasis on speed and accuracy have been found to produce higher information-processing rates than speed or accuracy emphasis (Howell and Kreidler 1963). Pursuing perfect accuracy was not encouraged because, given participants' overall high accuracy in numerical typing, small accuracy changes could generate very large differences in RT based on speed–accuracy operating characteristics (SAOCs) and is, therefore, unrealistic (Drury 1995).

Possible theories accounting for the origin of SATO were well discussed in the literature, yet consensus has not been reached (Wickelgren 1977, Wickens and Hollands 1999). In the case of urgent trials in rapid aiming movements, neuromotor noise could be a possible explanation of SATO (Van Gemmert and Van Galen 1997, 1998, Van Galen and Van Huygevoort 2000). Neuromotor noise theory stated that a perceptual–motor system is an inherently noisy system, and psychological stressors such as time pressure will enhance its noise. Noisy motor behaviours need effective biomechanical filtering to control resultant physiological tremors, and higher muscle stiffness utilised to facilitate muscular co-contraction will lead to faster movements. Speedy movements themselves are noisy, spatially variant and, thus, error-prone if the speed is pushed beyond a certain optimal point. Increased errors in urgent trials might also result from anxiety caused by high self-consciousness. High self-consciousness could lead to unnecessary attention to task-irrelevant information resulting in degraded performance of highly motivated participants (Nieuwenhuys *et al.* 2009).

The mental stress caused by urgency can raise concerns about typists' health due to its cardiovascular effects and musculoskeletal risks. Eubanks *et al.* (2002) examined cardiovascular effects of monetary reward found that the heart rate was influenced by incentive value only in the most difficult tasks, suggesting an interaction between task difficulty and monetary reward (Eubanks *et al.* 2002). Similar effects were found in the current study in terms of subjective temporal ratings but not performance. The increased subjective workload ratings could be, therefore, related to the increase of cardiovascular responses as internal efforts to cope with relatively difficult work so that performance could be maintained (Gaillard 1993). Other researchers also reported a close relationship between increased typing speed and increased typing force under time pressure, and the effects were more pronounced for typists who are symptomatic in musculoskeletal disorders (Szeto *et al.* 2005, Hughes *et al.* 2007). Hence, techniques such as deadlines and incentives that were used to compel workers to challenge their maximal work capacity may not necessarily improve productivity; Appropriate management policies should consider workers' internalised urgency caused by the task requirements together with any cardiovascular effects and musculoskeletal risks to avoid human errors and occupational disorders.

4.4. Patterns of typing errors

Several error phenomena in numerical typing revealed in this study were compared with Salthouse's findings (Salthouse 1986) for alphabetical typing in Table 4. An interesting observation is that transposition errors occurred even in the absence of two-hand alternation. Exclusive occurrence of transposition errors under the fast speech rate implied that delayed responses to the current auditory stimuli and precipitous responses to the subsequent stimuli might cause transposition errors. Failure in deactivating motor programs and faulty finger assignments were unlikely causes, because transpositions did not repeat the previous pair of digits and rarely were adjacent digits.

The spatial distribution of reaching difficulty showed a diagonal pattern of hand movement (Figure 9d) in which the '3' key and the '7' key were the most difficult keys to reach. Since the upper-left and bottom-right corners are the most difficult positions to reach, designers of the numerical keyboard may consider distorting the rectangular shape into a more diagonal one, so that the two difficult corners can be avoided. An alternative design could consider increasing sensitivity for difficult-to-reach keys and raising depression criterion for intrusion-prone keys (e.g. the '4' key) as they were revealed in Figure 9 and Appendix 1. Observations about error-prone keys also help us find spatial incidence of error occurrence and may contribute to error detection, e.g. paying more attention to error-prone digits.

4.5. *Limitations and future studies*

One limitation of this study is that only two levels of speech rates were tested. Obviously, neither fast nor slow speech rate tested was the optimal speech rate to maximise typing performance. A future detailed behaviour study that investigates full continuum of ISI would determine which cognitive processing created the bottle neck and which resource was subject to competition in numerical typing task under fast pacing. A modelling attempt could also quantitatively confirm speculative mechanisms proposed in this study. Other conjectures associated with biophysical reactions (such as urgency caused noisy muscle activity and SATO) need to be checked in experimental studies with appropriate measurements. A recent study in typing has confirmed that time pressure increased both finger muscle activity and key striking force, compatible with the authors' prediction of biophysiological responses during SATO based on neuromotor theory (Hughes *et al*. 2007).

Although the participants in this study were not taken from the work force, their numerical typing performance was comparable to skilled typists (Seibel 1977, Marteniuk *et al*. 1996). They could generate around 100 keys/min with over 90% accuracy in the pretest (Table 1), and, therefore, their perceptual–motor skills were expected to be representative of skilled working force. Generalisation of the results to working groups of different ages and typing skills, however, requires caution. Older adults showed reduced capacity to process perceptual information during an ongoing response and produced slower movements in tasks of higher complexity in the previous research (Tolin and Simon 1968). In addition, older adults tended to move slowly and relied more on correction phase of the movement to maintain the same accuracy level (Hsu *et al*. 1997, Nagasawa *et al*. 2000, Welsh *et al*. 2007). Therefore, fast pacing and greater complexity in typing could be more demanding to older participants, especially under urgency, because they can no longer rely on time-consuming correction if they want to success. Similarly, research also suggested that experienced typists may adopt more efficient muscle recruitment patterns without significant increase in muscle activity when they are required to type faster (Gerard *et al*. 2002, Szeto *et al*. 2005), while lack of typing expertise may lead to inefficient coping with urgency. SAOC also implies that typists with different expertise could demonstrate a different SATO, i.e. little improvement in speed may cause large degradation in accuracy. Delay of responses and degradation of accuracy might be more pronounced in urgency for older and less experienced typists. The general trend, i.e. fast pacing and greater response complexity, produced slow RT and low accuracy, while urgency produced fast RT but low accuracy, however, is not expect to change.

Finally, the numerical typing was performed on a standard numerical keyboard, and whether the results can be applied to other alternative numerical keypads, such as those found on cell phones, calculators or even the numerical keypads on touch screens, needs further investigation. For example, touch screen keyboards were found to be slower and subject to human errors (Sears 1991, Thomas and McClelland 1996), but their use in numerical typing context has never been compared with standard numerical keyboards in a precisely controlled experimentation. Due to limitations in sample population recruited, the extent of investigation to the factorial continuum, and the experimental measurements adopted, further studies conducted with biophysiological measurements from a real work force utilising various keyboard designs in non-traditional typing tasks are encouraged.

5. Summary and conclusions

This is one of the first studies of numerical typing errors, and the results showed that fast pacing, great response complexity and urgency are involved in making errors. Manipulation of speech rates of verbally presented numbers as the pacing factor caused delays in response and more typing errors, attributable to the ineffective multi-tasking and a cognitive bottleneck due to short ISI. Greater response complexity in multi-finger typing together with finger-enslaving effects also degraded both typing speed and accuracy. Urgency arose from monetary reward pertinent to typing performance improved typing speed at the expense of sacrificing accuracy. The results suggested that incentives (such as tangible rewards) and task demands (such as pacing) should not be used to compel typists to challenge their maximal capacity; otherwise their performance will be pushed beyond the optimum, and their occupational risks increase. In addition, the analysis of error patterns revealed that error-making mechanisms in alphabetical typing do not necessarily translate to numerical typing. Given that young working force with intact perceptual–motor capabilities participated in this study, their susceptibility to inappropriate pacing, high response complexity and urgency implies that the numerical typing could be more problematic to less skilled and older work populations. Use of alternative typing devices (e.g. touch screens) may also create new concerns in numerical typing tasks. The findings of this study thus underline the importance of future studies of numerical typing tasks performed by different working groups on various typing devices to improve human performance and system safety.

Notes

1. One may argue that the delay could have been generated from no concurrent manual tasks; that is, the subsequent manual movement has to wait until the completion of the current movement, and, therefore, the delay of consecutive tasks was caused by intra-modality interference rather than inter-modality. However, if the delay had happened at motor response stage, the duration of the movement would have been unreasonably long. See Appendix 2 for details.
2. Since there was no interaction between factors, it would be reasonable to stratify the errors by factorial pairs, i.e. single vs. multi-finger, fast vs. slow speech rate and urgent vs. non-urgent instead of comparing between eight factorial combinations to assure enough sample size (>30).

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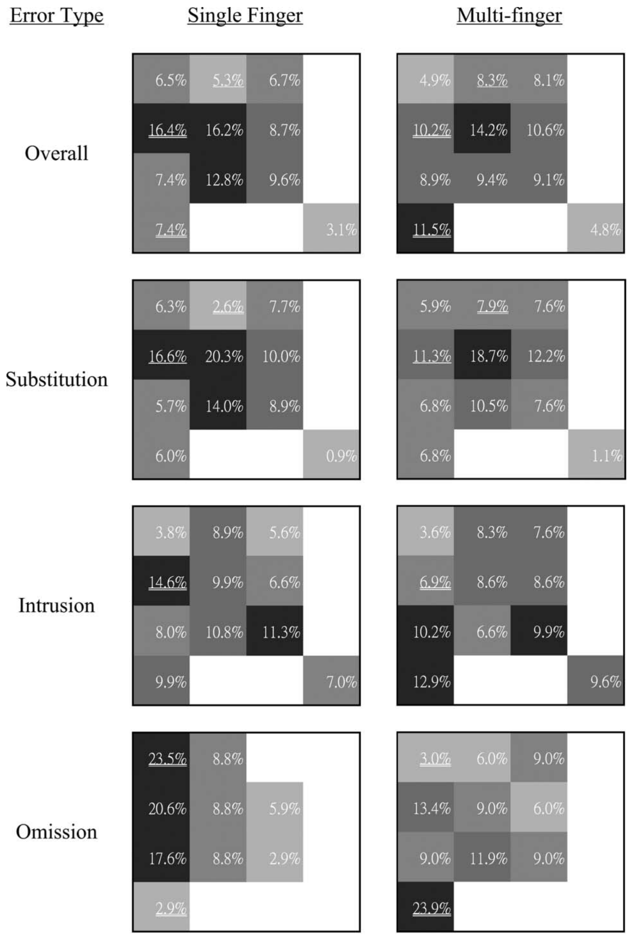
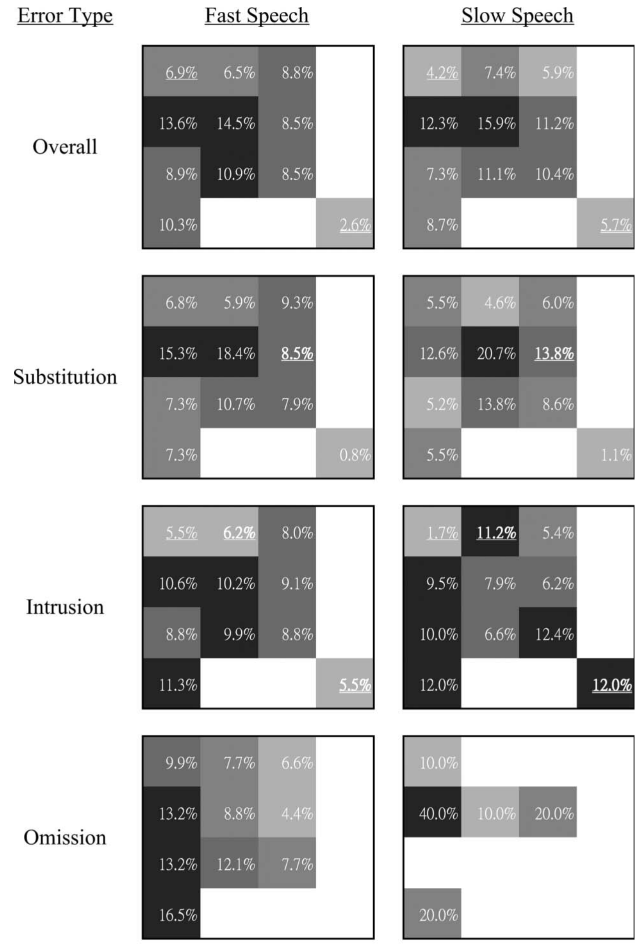
Appendix 1. Spatial incidence of different types of errors, stratified by experimental factors

The spatial incidence was stratified by factors to see their effects on errors.[2] [0]The pair comparisons for single vs. multi-finger typing are shown in Figure A-1. Overall, incidence of errors was significantly higher on the '4' key in single finger typing and on the '0' key in multi-finger typing. Further examinations by error categories showed that errors on the '4' key involved higher incidence of substitutions and intrusions in single finger typing, while errors on the '0' key included higher incidence of omissions in multi-finger typing. It was speculated that the proximity of the '4' key to the initial position of the index finger was the cause for higher incidence of substitution and intrusion errors in single finger



P<0.05 P<0.01 (Pair-comparison of single finger vs. multi-finger typing for the same key)

Figure A-1. Spatial incidence in single vs. multi-finger typing.



P<0.05 P<0.01 (Pair-comparison of fast speech vs. slow speech for the same key)

Figure A-2. Spatial incidence in fast vs. slow speech rate.

typing, while, in multi-finger typing, the depression force of the thumb was relatively weak to press the '0' key due to finger-enslaving effect (Jones and Lederman 2006), resulting higher incidence of omissions.

The comparison between fast and slow speech rate is plotted in Figure A-2. Apparently, fast speech rate caused significantly higher incidence of errors on the '7' key, and slow speech rate produced significantly higher incidence of errors on the 'enter' key. Further examination by error categories indicated that the higher incidence came from intrusions. The significantly higher incidence to press the 'enter' key unnecessarily might be associated with high anticipation of pressing the 'enter' key combined when there is a spare of time under slow speech rate.

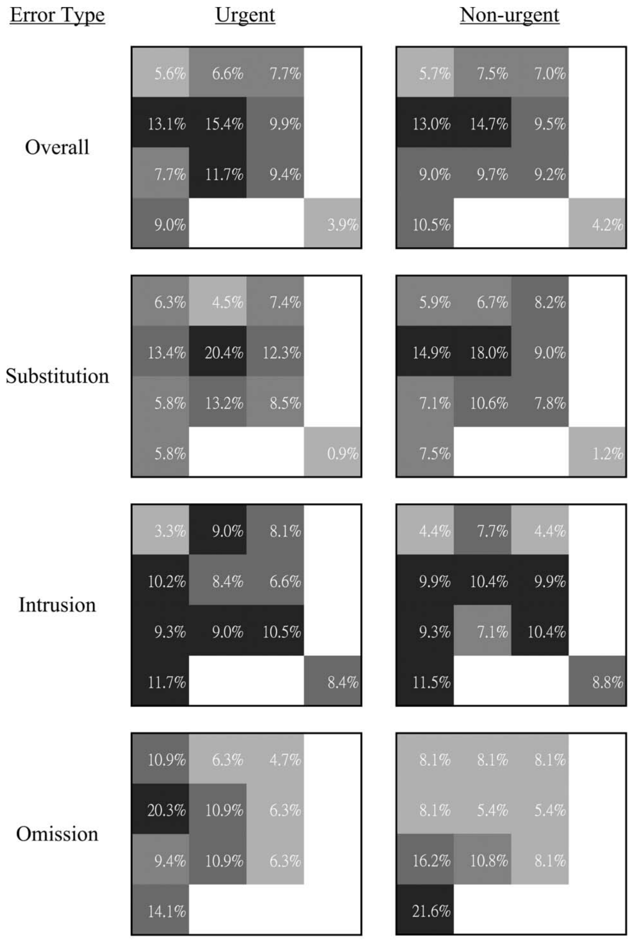
No significant difference of incidence was observed between urgent and non-urgent situation (Figure A-3), implying that manipulation of internalised urgency did not polarise spatial incidence. Unlike other manipulation of other external task demands which caused more or less spatial incidence patterns, urgency did not induce such patterns. Errors that are originated from urgency could be therefore more difficult to detect because no clue is available about which digit is more likely a wrongly typed digit.

Appendix 2. Derivation of movement time based on intra-modality scenario

Suppose RT $_i$ and MT_i are RT and movement time corresponding to stimulus i (S_i). Given that, in intra-modality scenario, bottle neck did not happen within RT_2 but outside RT_2 due to non-overlap of two manual tasks, suppose also that $RT_2 = RT_1$. D is the delay caused by the requirement of non-overlap. Since MT_2 is delayed only because it cannot overlap with MT_1, the initiation of MT_2 is logically assumed right after completion of MT_1. The delay can be thus derived based on the temporal relationship of S_1 and S_2 as follows:

$$\begin{aligned} RT_1 + MT_1 &= 500 + RT_2 + D = 500 + RT_1 \\ &\quad + D(\text{A1, also reference to Figure A}-4) \qquad (\text{A2}) \\ D &= MT_1 - 500(\text{A2}) \end{aligned}$$

Based on the experimental data, $D = 37.67$ and therefore $MT_1 = 500 + 37.67 = 537.67$ ms. This estimate is unreasonably long if compared to estimates based on either Fitt's law (Drury and Hoffmann 1992) or ballistic movements (Gan and Hoffmann 1988).



P<0.05 P<0.01 (Pair-comparison of urgent vs. non-urgent condition for the same key)

Figure A-3. Spatial incidence in urgent vs. non-urgent condition.

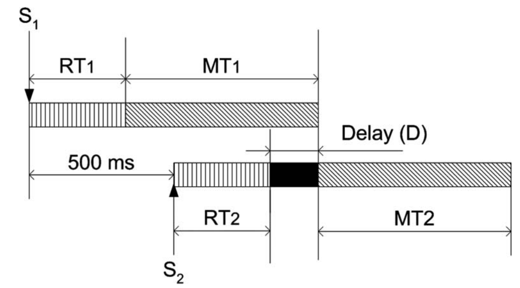


Figure A-4. RT diagram for intra-modality scenario.