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A Model of the Uncertainty Effects in Choice Reaction Time that Includes a Major Contribution from Effector Selection

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Abstract

Hick's law describes the relation between choice reaction time and the number of stimulus-response alternatives (NA). For over half a century, this uncertainty effect has been ascribed primarily to the time taken to map a stimulus to its associated response. Here, data from two experiments suggests that selection of the appropriate effector – the particular body part to make a response – also contributes substantially to the uncertainty effect. This insight is important both for our understanding of basic cognitive architecture and because many classic experiments studying stimulus-response mapping have confounded NA with the number of effectors. Our data also suggest that, when stimuli are spatial and linked to the responses in an intuitively simple layout, the time required for stimulus-response mapping depends minimally on the NA, independent of effector. Experiment 1 demonstrated that in order to account for the complex patterns of uncertainty effects observed when stimulus type (spatial versus symbolic), response mode (typing, with multiple effectors versus touching with a single, known effector), and participant population (skilled versus novice typists) are all manipulated a model is required that includes effector selection, along with stimulus-response mapping, and a proper treatment of stimulus-response repetitions. Using spatial indicator stimuli that minimized the contributions of stimulus-response mapping, Experiment 2 compared four effector conditions – the factorial combination of one or three fingers on one or both hands. The results showed that the increase in the uncertainty effect associated with the number of effectors is negatively accelerated and possibly additive across the variation of hands and fingers.

In a typical choice reaction time task, a set of stimuli is associated with a set of responses, usually with a one-to-one mapping of stimuli onto responses. A stimulus is presented on each trial and the P's task is to make the corresponding response. When the stimulus is clear and distinct, accuracy in this task is usually high, and so reaction time is the primary dependent measure. In such tasks, reaction time typically has been found to increase linearly with the logarithm of the number of potential stimulus–response alternatives, N_A, a regularity commonly known as Hick’s law (Hick, 1952; Hyman, 1953; see Proctor & Schneider, 2018, for a recent review). Although the size of this uncertainty effect depends on the stimuli, the responses used, and the mapping between them, as well as the level of practice, typically there is an increase of 100 - 150 ms for each doubling in the number of alternatives (bits). Although this paper will focus on performance in situations for which low error rates are normal, it is worth noting that a variant of this regularity also holds when error rates are larger. For example, Pachella and Fisher (1972) used a deadline procedure to study performance for several levels of N_A. When N_A and a P’s error rate in a condition were combined to produce a measure of information transmission in bits, this measure was found to be linearly related to median reaction time. Intriguingly, the slope of the function relating reaction time to bits of information transmitted estimated using deadlines to manipulate the speed-accuracy tradeoff is quite similar to that estimated in the more common procedures in which errors are minimized and N_A is varied (Pachella & Fisher, 1972, p. 381).

Why should we be interested in a task as basic as the choice reaction task? Alan Newell, in his ground-breaking book *Unified Theories of Cognition* (1990), put this task into the class of what he labelled “immediate behaviors,” those in which responses are made quickly, within roughly one second. He argued that immediate behaviors are of particular interest because they reveal the nature of the cognitive architecture: here “you can see the cognitive wheels turn and hear the cognitive gears grind” (p. 236). From this perspective, a correct understanding of the sources of the uncertainty effect is important for what it tells us about how the human brain has evolved to solve this class of basic tasks. More practically, such an understanding may prove crucial to developing the ability to interpret EEG signals that will be necessary to support the use of these signals to control prosthetic devices for the handicapped or in other applications of direct control of external devices by thought. It is also of practical importance that, within the realm of immediate behaviors, the uncertainty effect is very large, especially when one considers that the other components of reaction time that do not vary with N_A are typically 300 ms or less. When controlling complex devices, operators are often faced with choices that can be seen as analogous to a choice reaction task. Consider a pilot responding to a warning light requiring an action who must select the correct switch to activate in response from the rows of switches in an airplane cockpit. Clearly, a better understanding of how uncertainty effects depend on task characteristics could have important design implications for such real-world tasks.

For over fifty years, the accepted explanation of the uncertainty effect has implicated primarily the stimulus-response (S-R) mapping process (Teichner & Krebs, 1974). In some situations, stimulus identification clearly can also play an important role (Brown, Steyvers, & Wagenmakers, 2009), and indeed, many early accounts of the uncertainty effect focused on stimulus identification (see Smith, 1968 for a review); however, when the stimuli are easily discriminated and performance is nearly error free, the contribution of stimulus identification to reaction time appears to be constant rather than dependent on N_A. Consistent with the S-R explanation, it has generally been found that the size of the uncertainty effect increases for tasks with low S-R compatibility and that the effect is minimized for tasks with high S-R compatibility (Teichner & Krebs, 1974; Duncan, 1978; Dassonville, Lewis, Foster, & Ashe, 1999).

Recently Schneider and Anderson (2011) proposed a new way to understand the S-R mapping process instantiated as a model based on the ACT-R architecture (Anderson, 2007; Anderson et al., 2004). This model successfully reproduces important aspects of the data in an impressively broad array of classic papers, capturing variations in reaction time due to set size, practice, and stimulus-response repetitions, using the combination of just two mechanisms, both of which have been developed in other contexts: the associative interference that occurs during retrieval of S-R mappings from declarative memory and the savings that occasionally occur for stimulus–response repetitions when the retrieval process is bypassed. This model also has led to novel predictions that have been confirmed. Interestingly, this model does not predict a linear relation between reaction time and log(N_A), but rather a power-law type relation that, in practice, may be difficult to distinguish from a logarithmic one.

Exploring Boundary Cases: Situations in which Uncertainty Effects are Absent

Against this background, several situations in which uncertainty effects are absent may be revealing. Kveraga, Boucher, & Hughes (2002), for eye movements, and Wright, Marino, Belovsky & Chubb (2007), for aimed, hand movements, reported data where reaction time was observed to be independent of the number of possible stimulus-response pairs[i]. Both of these papers also reported data from conditions in which an identical stimulus arrangement led to a large uncertainty effect for spatially-compatible, keypress responses. This pattern of results presents a challenge for the standard interpretation that uncertainty effects are due primarily to effects of the S-R mapping process even with the caveat that S-R effects can be modulated by practice (Teichner & Krebs, 1974). The traditional button-pressing task pairs an array of lights as the stimuli with an equal number of pushbuttons for the responses. Each button is located directly below the single light for which it is the response. When a light flashes on, the P responds by depressing the finger placed on the button directly below that light. As in the two papers just cited, this task has been found to produce uncertainty effects of well over 100 ms per doubling in the number of alternatives (Brainard, Irby, Fitts, & Alluisi, 1962; Hick, 1952); however, the required S-R mapping seems maximally simple and straightforward. Given that the two tasks possess highly compatible S-R mappings and are distinguished only by the response required, it is difficult to explain the change from zero to a large uncertainty effect based solely on S-R compatibility. To add to the puzzle, these two papers are not the first instance of a dramatic change in the size of the uncertainty effect that has been observed to depend on the response modality. As summarized in the meta-analysis of Teichner and Krebs (1974), keypress responses to visually-presented letters or digits have a large uncertainty effect; however, if responses are instead made by naming the digits there is little or no uncertainty effect (Brainard et al.,1962; Mowbray, 1960). Interestingly, letters and digits appear to be special in this regard; when a task involves naming familiar colors, animals, and faces, there is once again a substantial uncertainty effect (Morin, Konick, Troxell, & McPherson, 1965).

Various explanations have been offered to explain the absence of a large uncertainty effect in the examples cited above. Kveraga, Boucher, & Hughes (2002) suggested that mechanisms in superior colliculus, available only to eye movements, can bypass the normal S-R mapping process. However, this explanation is undermined by a similar lack of uncertainty effects for touching movements. Wright, Marino, Chubb, & Rose (2011) investigated, but ultimately rejected, exogenous attention as an explanation for the lack of an uncertainty effect observed for both eye movements and touching movements. Specifically, they hypothesized that when a stimulus draws attention to itself, eye and hand movements to that stimulus may be automatically prepared, thus bypassing the S-R mapping process. Contradicting this suggestion, two experiments found that replacing the indicator stimuli used in previous research – filling in of an outline circle at the target location – with indicator stimuli that do not draw attention – either filling in of all the non-target circles or an arrow, at fixation, pointing to the target circle – did not change the results: there was still no uncertainty effect for touching responses. Practice is also offered as an explanation for the large differences in the size of the uncertainty effect across tasks. A meta-analysis of choice reaction time data reported by Teichner and Krebs (1974) supports this explanation. Their analysis showed that uncertainty effects are systematically reduced with practice for both the light-button task discussed above and for a task in which buttons are associated with visually presented digits. Furthermore, an extrapolation of the learning functions they assembled suggests that the uncertainty effects would have largely disappeared had practice continued for several million trials. Although such extrapolations are always dangerous, the general point is well taken: uncertainty effect size is reduced with practice, and this reduction presumably reflects increased automaticity of the S-R mapping process. Perhaps, although the mapping of the light-button task seems natural, the uncertainty effect for this task is large simply because this task is not one we do in our daily lives nearly as often as touching or making a saccade. If this explanation is correct, the results of Kveraga et al. (2002) and Wright et al. (2007), as well as those for digit naming, can be explained by differential experience without the need to consider anything about the nature of the responses being made.

From a different perspective, Schneider and Anderson (2011) suggested that many of the instances of null or negligible set-size effects, such as those cited above, involved situations in which the S-R mappings are sufficiently direct that Ps “do not require access to stimulus–response associations in memory” (p. 198). In their discussion, Wright et al. (2011) proposed an elaboration of this idea that will be central to this paper. They focused on the large difference in size of the uncertainty effect found when comparing the light-button task with compatible mappings to tasks that require either touching responses or saccades with similarly compatible S-R mappings. While acknowledging that S-R compatibility, S-R repetition, and practice are important contributors to uncertainty effects, they suggested that the critical task difference is that effector selection contributes to the size of the uncertainty effect in the traditional light-button task but not in the tasks using touching or saccade responses, for which the response effector is known before the stimulus is presented. A specific elaboration of this suggestion is the hypothesis that uncertainty effects close to zero are only observed when S-R compatibility is high and the effector to be used to make the response is known in advance. Both requirements are true for tasks in which the response is a saccade or moving a fixed body part to touch a

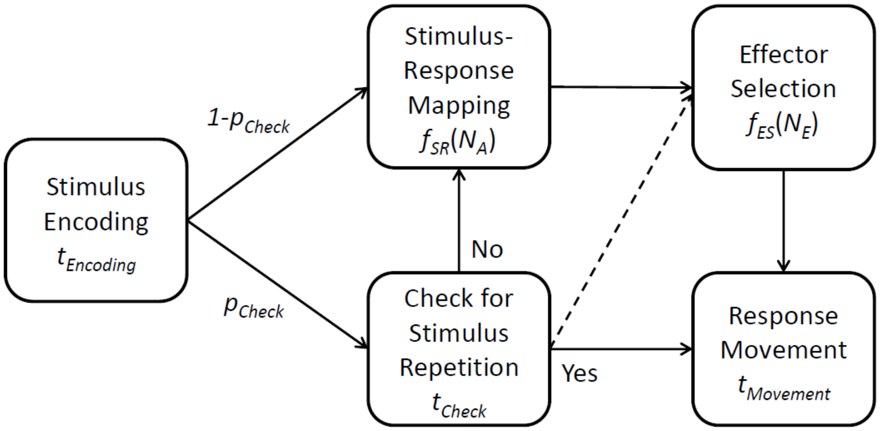

Figure 1: Possible stage model for choice reaction time tasks including effector selection. Based on Schneider & Anderson (2011).

stimulus location that is also the target location for the response. It can also be argued that these conditions hold for overlearned vocal tasks, such as digit naming, since overlearning leads to high S-R compatibility, and, if the vocal system is an effector, it is known. But note, it is not a vocal response alone that eliminates uncertainty effects. For example, Hyman (1953), studying vocal responses (*bun, boo, bee, bore, by, bix, bev, bate*) arbitrarily associated with the onset of specific lights in a square layout found uncertainty effects of 173 ms per doubling of the number of S-R pairs, perhaps because this is a task for which S-R compatibility is low. Of particular importance for this paper, requiring to befor the traditional light-button task, in which each response is made by a different finger and so the response effector – i.e., the particular finger – cannot be known prior to viewing the stimulus and the number of effectors, N_E, is confounded with N_A, the number of stimulus-response alternatives.

A Proposed Model that Includes Effector-Selection

Figure 1 is a diagram of a proposed stage model for the choice reaction time task that includes our hypothesized, effector-selection stage, separate stages for both stimulus encoding and S-R mapping, and a provision for the processing of S-R repetitions based on the model of Schneider and Anderson (2011). S-R repetitions, which occur when the same S-R combination occurs on successive trials, represent both a complication for the interpretation of choice reaction times and, as we will argue later, a potential window into the operation of the mechanisms underlying uncertainty effects. Ps are generally faster to respond on repetition trials (for reviews supporting this point see Kornblum, 1973, or Luce, 1986, chap. 10). This creates a complication when, as in experiments studying Hick's law, N_A varies because, for example, when there are two possible targets, repetitions are three times more likely to occur than when there are six possible targets. Thus, when analyzing these data, simply collapsing over repetition and switch trials artificially inflates the size of the uncertainty effect (Kornblum, 1968 & 1969).

The initial processing step of the model shown in Figure 1 is stimulus encoding. Because we are focusing on situations involving clear, distinct stimuli for which close to error-free performance is possible, it is reasonable to represent the time required to complete this step by a constant,

$t_{Encoding}$: i.e., although this duration might be expected to differ for different types of stimuli, it is assumed to be independent of both N_A or N_E. Although a potentially reasonable simplification, it must be noted that this assumption does not necessarily apply when stimuli are either obscured by noise or are easily confusable. For example, Leite and Ratcliff (2010) report two experiments in which one of a set of 2, 3, or 4 letters, chosen for their lack of confusability, was identified by moving a finger ($N_E = 1$) to an associated response key. In this task, reaction times appeared to increase logarithmically with N_A. The error rates were high, however, ranging from almost 10% in the easiest condition, with $N_A = 2$ and the smallest level of visual noise, to about 35% in the hardest condition, with $N_A = 4$ and the smallest level of visual noise. We could not find any papers that manipulated the confusability of stimuli and N_A; however, in his extensive review, Smith (1968) cites a meeting paper by Chase and Posner (1965) that varied the visual similarity between stimuli in a yes/no task. In this experiment, the slope of the reaction times increased with the similarity of the stimuli.

In contrast to these perceptual effects on the stimulus encoding stage, Brown and his colleagues (Brown, Steyvers, & Wagenmakers, 2009; Hawkins, Brown, Steyvers, & Wagenmakers, 2012) have documented what might better be understood as cognitive effects on stimulus encoding. Inspired by the extensive literature on accumulator models (discussed below), they looked at multi-alternative decisions made when Ps observe evidence for different alternatives accumulating visually over time. In this paradigm, the “accumulators” are demarcated regions of the display screen. The evidence accumulated is represented by small blocks added randomly to each accumulator in discrete time. P’s task is to choose the target accumulator that is filling faster than the others. Set size is manipulated across trials by varying the number of accumulators. Brown et al. found that response latency varied with N_A in accordance with Hick’s law. Hawkins et al. subsequently showed that the effect of N_A on the error rate depended on whether N_A was varied within or between Ps. When N_A was varied within Ps (Brown et al. and Hawkins et al., Experiment 2) the latency increase was accompanied by a dramatic decline in accuracy (from about 90% with two alternatives to less than 60% with 20). However, when N_A was varied between Ps (Hawkins et al., Experiment 1), accuracy was constant, and the logarithmic increase in reaction time had a substantially steeper slope. The reason that we do not dwell further on this result is that the latencies involved are much larger than those associated with the immediate behaviors that are, traditionally, the focus of Hick’s law studies: when N_A was varied between 2 and 20 within Ps, latencies ranged from 7s to over 15s; when N_A was varied between Ps, the latencies ranged from 7s to over 25s.

The second stage along the upper processing path in Figure 1 is S-R mapping. This stage has been the primary focus for most studies of the source of uncertainty effects. In Figure 1, the time required for this stage to complete is shown as a function of the number of stimulus-response alternatives, $f_{SR}(N_A)$. In a tradition growing out of information theory, Hicks (1952) suggested that the negatively accelerated function that is typically observed be modeled as a logarithm and considered several processes that would give this functional form. Proctor and Schneider (2018) give an excellent account of the long history of challenges to the information theoretic approach, the process-model interpretations proposed by Hick and others, and the exact form of the relationship. In recent years, one major effort has been to explore whether and how multi-alternative accumulator models should be structured, not only to reproduce the logarithmic form of Hick's law, but the observed distribution functions for reaction times and errors (Usher & McClelland, 2001; Usher, Olami, & McClelland, 2002; Brown, Steyvers, & Wagenmakers, 2009; Leite & Ratcliff, 2010). A different approach, is the memory-based model of Schneider and Anderson (2011) that was described earlier. According to this model, $f_{SR}(N_A)$ should take the form of a power function. This model has a strong theoretical basis and Schneider and Anderson show that the power function may account for some data better than logarithms. However, for the questions addressed in this paper, either formulation could be used, and, for simplicity of presentation, we will use the logarithm base 2 and restate $f_{SR}(N_A)$ as a linear function of this logarithm,

$$f_{SR}(N_A) = t_{AddSR} + b_{SR} \log_2 N_A, \tag{1}$$

where t_{AddSR} is an additive constant and b_{SR} is the slope.

The third stage in the upper pathway of Figure 1 is our proposed addition to the choice reaction time model, effector selection. In previous models, if this stage is considered at all it is lumped with our fourth stage, the production of the movement response, and dismissed as being of little interest. For example, Smith (1968) says that after the stage that does response selection is a final stage in which the response is programmed and notes that: "none of the theories has dealt with the last stage (nor has the preceding empirical review)" (p. 86). In our formulation, the duration of the effector selection stage is assumed to be a function of the number of possible effectors, $f_{ES}(N_E)$ but independent of N_A. We suspect that $f_{ES}(N_E)$ like $f_{SR}(NA)$ is a negatively accelerated function, since this would help to explain why, in previous research, the relationship between reaction time and N_A has a similar form when N_A and N_E are confounded and in pointing tasks, involving complex S-R mapping, for which $N_E = 1$. Although Experiment 1 will not provide a good evaluation of this claim, Experiment 2 will be somewhat more useful from that perspective. So, with the understanding that this is tentative, we will also use the logarithm base 2 for the form of $f_{ES}()$ and restate $f_{ES}(N_E)$ as a linear function,

$$f_{ES}(N_E) = t_{AddES} + b_{ES} \log_2 N_E. \tag{2}$$

where t_{AddES} is an additive constant and b_{ES} is the slope.

The last stage for both the upper and lower pathways includes everything else involved in initiating the movement required to make the response associated with the stimulus. Although the time required to complete this step, $t_{Movement}$, may differ for different response modalities, the duration of this stage is assumed not to depend on N_A or N_E.

Following Schneider and Anderson (2011, Eqs. 14 and 15), processing to detect stimulus-response repetitions occurs only on a fixed proportion, p_{check}, of trials. We have just described the processing sequence assumed to occur on the $1 - p_{check}$ trials without repetition checking. The processing sequence is more complicated on the p_{check} proportion of trials that include repetition checking. It is important to understand that the choice to check for a repetition is modeled as being a random one that is independent of whether or not a S-R repetition has occurred. The time required for this process, t_{check}, is assumed not to depend on whether or not a repetition was detected or on N_A or N_E. When a repetition is not detected, processing continues with S-R mapping stage as described above, and reaction time is expected to differ from that for the normal path only by the addition of t_{check}. Schneider and Anderson (2011) suggest that detection of a repetition allows the processing to bypass the memory retrieval process that instantiates the S-R mapping stage in their model; it is unclear, however, whether the effector-selection stage also should be bypassed. Figure 1 contains arrows indicating two possibilities for how processing continues. One of these possible paths leads back to effector selection, implying that only S-R mapping is bypassed. The second leads to the response-movement stage, implying that detection of a repetition allows processing to bypass both S-R mapping and effector selection. The data we will present suggest that the second of these alternatives is the correct one, which is why it is shown in Figure 1 with a solid arrow and the first alternative is shown with a dashed arrow.

By tracing the possible paths through Figure 1 and accepting the “pure insertion” assumption (cf. Sternberg, 1969 & 2001), we can derive equations predicting mean reaction time. It is convenient to write separate equations for switch trials, those in which the stimulus and the response differ from those of the previous trial,

$$RT_{Switch}(N_A, N_E) = t_{Add} + p_{check}t_{check} + b_{SR}\log_2 N_A + b_{ES}\log_2 N_E \tag{3}$$

and repeat trials, those in which they are the same,

$$\begin{aligned} RT_{Repeat}(N_A, N_E) = {} & t_{Add} + p_{check}t_{check} \\ & + (1 - p_{check})[b_{SR}\log_2 N_A + b_{ES}\log_2 N_E] \end{aligned} \tag{4}$$

For compactness, both equations include the new term, $t\_Add = t\_Encoding + t\_AddSR + t\_AddES + t\_Movement$. This consolidation of terms is reasonable because the design of our experiments will not provide data that can be used to estimate separately the additive components that make up t_{Add}.

Although this model identifies no specific locus for the effects of practice, we can offer a speculation. For typical choice reaction time tasks, we expect the majority of the reductions in time due to practice to be localized in the two slope coefficients, b_{SR} and b_{ES}. We do not expect large practice effects on the components of t_{Add} when, as here, the stimuli and the mode of responding are highly familiar to Ps; it is the mapping of stimuli to responses and of responses onto effectors that are potentially novel and thus more likely to improve with practice. The same logic also argues against p_{check} or t_{check} as the locus of practice effects. We would expect the mechanisms that bypasses S-R mapping and effector selection upon the recognition of a repeated stimulus to be generic to these situations – and thus already overlearned – rather than specific to a particular task.

Experiment 1

The primary goal of this experiment is to test the hypothesis that effector selection is a separate process requiring a non-trivial amount of time that depends on the number of possible effectors, N_E. If this hypothesis is correct, then the time required for effector selection may explain the instances, described previously (Kveraga, Boucher, & Hughes, 2002; Wright et al. 2007), in which large differences in the size of the uncertainty effect appears to depend only on changes in the way that responses are made. Exploring this hypothesis is important for several reasons. If correct, it suggests that an important component of immediate behaviors has been largely ignored. Understanding the role of effector selection also may unravel some complications in the literature on stimulus-response compatibility because some experiments in that literature involve responses made with only a single, known effector, but many more confound effectors and stimuli. From an applied perspective, progress in either of these areas has the potential to lead to important practical applications.

In order to eliminate other explanations for the large uncertainty effect differences and to allow a better characterization of effector selection, this experiment will also manipulate the compatibility of the S-R mapping and, using a between-groups comparison, the degree of prior practice with a non-trivial S-R mapping. To that end, we report data from two groups of participants who each provided data in four tasks. Within each task, two levels of uncertainty (N_A) were studied: there were either two stimulus-response pairs or six. The four tasks were constructed by combining two types of visual stimulus and two response methods as shown in Table 1 and illustrated in Figure 2. For both types of visual stimulus, the initial screen showed a set of either two or six, out of a possible 8, white outline circles arranged in a semi-circle surrounding a fixation mark on a computer monitor. This set of circles, which indicated the possible S-R pairs, remained fixed for a block of trials. In a subsequent stimulus frame, the indicator stimulus identified the actual stimulus and thus the required response from the displayed set. In tasks using a spatial stimulus, the indicator stimulus consisted of one of the outline circles filling in to become solid white. This stimulus is functionally similar to one of a set of lights turning on in the classic, light-button task. The Symbolic indicator stimulus was a letter displayed at fixation. Each of the eight possible stimulus locations had a letter associated with it. These were the letters “A S D F J K L ;” – i.e., the letters on the “home” finger positions for touch typists using a QWERTY keyboard.

As shown in Table 1, the two response methods, Keypress versus Touch, differed in how the number of effectors, N_E, varied as N_A varied. Responses in the Keypress condition were made on a keyboard by different fingers, so $N_E = N_A$ and the number of S-R alternatives was confounded with the number of effectors, as in the classic light-button task. Touch responses are made using a single, handheld stylus, so $N_E = 1$.

Table 1: Summary of the four tasks studied.

	Stimulus Type		
Response	Spatial	Symbolic	**Mapping**
Keypress	Novel but natural	Well Practiced for touch typists	$N_E = N_A$
Touch	Well Practiced	Novel	$N_E = 1$

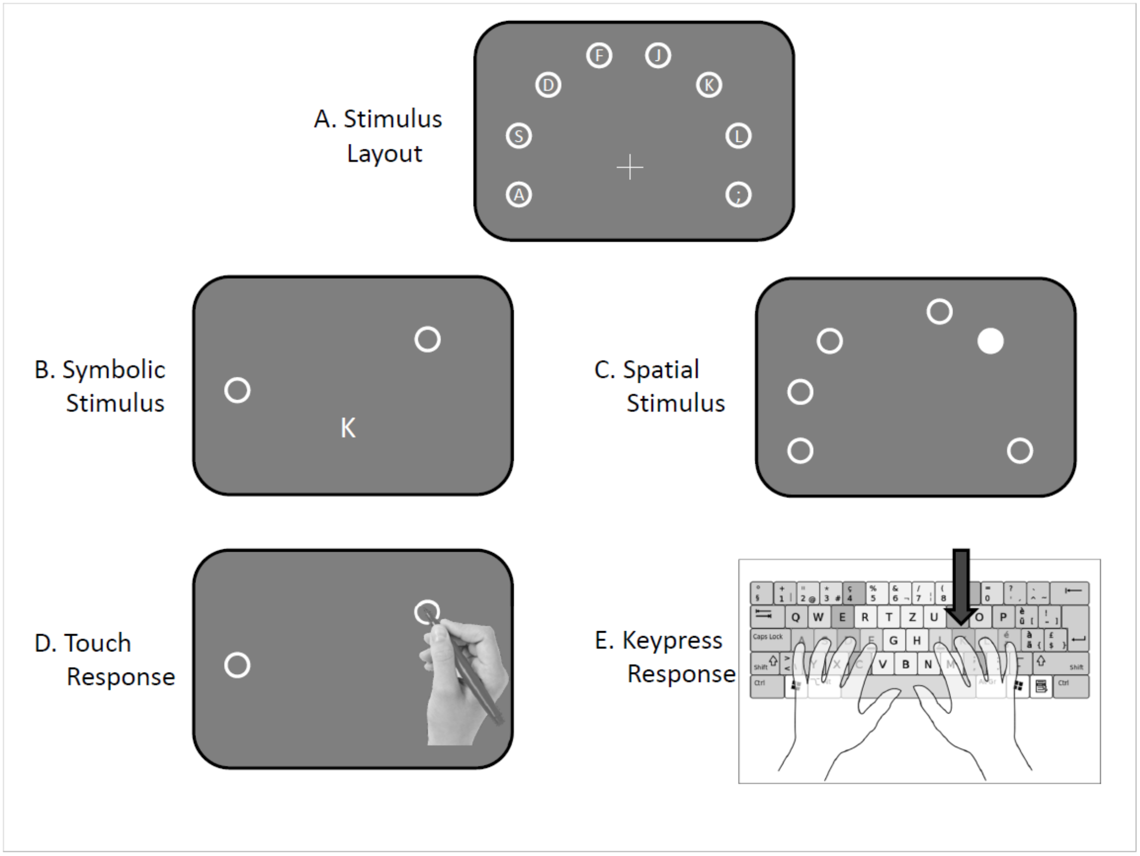

Figure 2: Stimulus layout and an overview of the four tasks. Panel A shows the layout of the eight possible spatial stimulus locations, which were also response targets for touching responses, and the symbolic stimuli associated with the eight locations. Panels B and C illustrate the two indicator-stimulus types, symbolic and spatial. Panels D and E illustrate the two response types. The combination of Panels B and D shows a possible sequence of events in the condition with symbolic indicator stimuli and touching responses on a trial with $N_A = 2$. The indicator stimulus, K, appears at fixation. Because this indicator stimulus is associated with the target location on the upper right, the participant moves the stylus to touch that location. Panels C and E similarly illustrate the events in the condition with spatial indicator stimuli and keypress responses on a trial with $N_A = 6$. Here the indicator stimulus is a filled in circle. The P responds by pressing the K key on the keyboard since that is the response associated with this location.

Figure 2A shows the fixed mapping that linked the two indicator stimulus types: symbolic letters and spatial locations. Although this mapping was unfamiliar to our subjects, it was easily learned. As summarized in Table 1, this is important because the combinations of stimulus types and response methods included one potentially familiar combination for each stimulus type and each response method and one clearly less familiar combination. Touching a specific location in response to a Spatial indicator stimulus is a task that should be generically familiar for all Ps. However, touching that same location, in response to a Symbolic indicator stimulus – i.e., a letter whose association with the response location is only learned within the experiment –

involves an S-R mapping that should be novel for Ps. Similarly, responding with the correct one of several possible effectors (fingers) to press the key on the home row of the keyboard associated with the location of the Spatial indicator stimulus is task that should also involve a novel S-R mapping for Ps, but one that is very natural. In contrast, to press the same key in response to a symbolic indicator stimulus involves an S-R mapping – i.e., that between letters and the keys on the QWERTY keyboard home row – that should be overlearned for at least experienced, touch typists.

To take advantage of the potentially important variation in the familiarity of the S-R mapping for the task pairing symbolic stimuli with a keypress response – in essence, a simple typing task – the Ps were drawn from two groups according to their typing skill. The "novice" typing group consisted of Ps for whom keyboarding was a well-learned task but were hunt-and-peck typists with low measured typing speeds. The expert typists were touch typists, for whom the S-R mapping is arguably highly overlearned given their fast, measured typing speeds.

Predictions Based on the Model

Because Experiment 1 will include only two levels of uncertainty ($N_A = 2 \text{ and } N_A = 6$), much of what is of interest in the data can summarized by the uncertainty contrast, computed for each of the four tasks as $U = RT(N_A = 6, N_E) - RT(N_A = 2, N_E)$. An advantage of focusing on uncertainty effects is that taking this difference eliminates many of the other terms in Equations (3) and (4). So,

$$U_{Switch} = b_{SR} \log_2(3) + b_{ES} \Delta N_E \qquad (5)$$

$$U_{Repeat} = [b_{SR} \log_2(3) + b_{ES} \Delta N_E](1 - p_{check}) \qquad (6)$$

In these equations, the multiplier of b_{SR} is $\log_2(3) = \log_2(6) - \log_2(2)$. Similarly, the multiplier of ΔN_E, b_{ES}, is either $\log_2(3)$, in the keypress tasks where $N_E = N_A$, or 0 in the touching tasks where $N_E = 1$.

Focusing on uncertainty effects allows two important observations. First, Equation (5) shows that, across the four tasks, differences in the sizes of uncertainty effects for the switch trials depend only on the additive effects of S-R mapping and effector selection, and so this contrast provides a clean estimate of the sum of these effects. Second, for any given task, the uncertainty effect for the repeat trials is decreased by the factor $1 - p_{check}$ in comparison to switch trials. In the analysis for this experiment, this relation will be used to assess the assumption, which underlies Equations (3) and (4), that successfully detecting a stimulus repetition bypasses both the S-R mapping and the effector selection stages. This same analysis will be used to explore the stability of p_{check} across tasks and Ps; it turns out to be remarkably stable.

The analysis of the reaction time data from this experiment will be based on the model outlined in Equations (3) and (4). The important conclusions will be derived less from whether this model fits well – although it does – and more from how well the estimates of b_{SR} and b_{ES} across conditions agree with the following set of predictions. In outlining these five predictions, we will use superscripts composed of abbreviations to refer to the values of b_{SR} and b_{ES} in particular tasks. The abbreviations used to refer to the two stimulus conditions will be *Sym* and *Spat*; the abbreviations for the two response methods will be *Key* and *Touch*. So, for example, b_{SR}^{SymKey} stands for the increase associated with S-R mapping for a doubling of N_A in the task using a symbolic indicator stimulus and keypress responses. Similarly, b_{ES}^{Spat} stands for the increase associated with effector selection for a doubling of N_E in the tasks using a spatial indicator stimulus.

$(1)\ b_{ES}^{Key} \gg 0$. This prediction is listed first because it is the central tenet of our proposal: i.e., in choice reaction time tasks, there is an increase in reaction time associated with the number of effectors and this increase is large by the standard of uncertainty effects. It will, unfortunately, not be possible, in the context of this experiment, to test the implicit assumption that the contribution of effector selection to the uncertainty effect is identical for tasks using spatial and symbolic indicator stimuli. However, this would be expected if this stage is truly separate from and follows after S-R mapping. If this assumption is badly violated, however, it should show up in odd values for the other parameter estimates.

(2) b_{ES}^{Key} should be smaller for expert than for novice typists. This follows from the expectation that expert typists have substantially more practice selecting between their hands and among their fingers to make responses and that practice reduces the time for both S-R mapping and effector selection.

(3) $b_{SR}^{Spat} \cong 0$. Although this is what we will assess, there are two parts to this claim and thus two ways that it might fail. The first part is that $b_{SR}^{SpatTouch} \cong 0$, i.e., that there should be little or no S-R mapping cost in tasks that involve touching locations determined by a spatially compatible indicator stimulus; this prediction is consistent with the results of our previous studies (Wright, Marino, Belovsky & Chubb, 2007; Wright, Marino, Chubb, & Rose, 2011). The second part of this claim, that $b_{SR}^{SpatKey} \cong 0$, is consistent with the suggestion made by Wright, Marino, Chubb, & Rose (2011) that the uncertainty effects observed in tasks that involve keying responses on keys compatibly mapped to a spatial indicator stimulus are due to effector selection, not S-R mapping, when, as here, the S-R mapping is highly compatible.

(4) $b_{SR}^{SymTouch} \gg 0$. This prediction is consistent with the classic explanation of uncertainty effects: i.e., that there is an S-R mapping cost for responses involving unfamiliar S-R mappings. Certainly, there is no reason to expect the mapping of letters onto movement target positions on a display screen has been practiced previously by the Ps. Since the symbolic stimuli are the letters on the home row of the standard QWERTY keyboard, and the spatial layout of the target positions resembles a horseshoe-shaped home row, one might expect this uncertainty effect to be smaller for Expert than for Novice typists, but this is hardly a central prediction of our proposal.

(5) b_{SR}^{SymKey} should be much larger than zero for novice typists, but smaller and possibly close to zero for expert typists. This prediction makes sense given the well documented observation that the cost of S-R mapping is reduced through extensive practice. Presumably, the expert typists are skilled at mapping the symbolic indicator stimuli used in this task, the letters on the home row of the QWERTY keyboard, onto the corresponding keys on the home row. In this day and

age, responding to a letter with a key is hardly a novel task for our novice typists; nonetheless, judging from their measured skill level and the observation that they are not touch typists – i.e., that they type with one, two, or three fingers – they are presumably much less practiced at the S-R mapping required by this task. One caveat to this argument is that the primary skill practiced by our expert typists is copy typing, and, although similar in some ways, single-letter typing might be sufficiently different from copy typing that their heavily practiced skill does not transfer well.

Methods

Participants

There was a total of 16 participants (5 male, 11 female). Each had vision that was at least correctible to 20/20, and all were all right-handed. As described below, eight were selected because they were highly skilled touch typists and the other eight because they were not. They were paid $8/hour and given small, performance-based bonuses. The UCI Institutional Review Board approved the experiment.

To assess their typing speed, all Ps were asked to complete an online typing test (http://www.typeonline.co.uk/typingspeed.php). Ps with a measured, raw typing speed over 70 words per minute were categorized as experts and those with measured typing speed below 50 words per minute and who were not touch typists – i.e. they used only two or three fingers to complete the typing test – were categorized as novice. Ps with measured typing speed between 50 and 70 were not used in this study.

Apparatus

A PC running a custom application written in C was used to present stimuli and record responses. A Dell Model M991 CRT display, running at a 60 Hz refresh rate with 1024 x 768 pixels was used to present all stimuli. This monitor was mounted within a specially built desktop so that its surface was angled up from horizontal by 20°. On keypress-response trials, a Dell keyboard, connected to the PC was used to register the responses. On touch-response trials, Ps used a handheld, lightweight stylus to touch the target on the monitor, (see Figure 1 of Wright, et al., 2007, for a photograph showing the experimental setup). An Optotrak Model 3020 recorded the x, y, and z coordinates of an infrared emitter mounted on the tip of the stylus with a 100 Hz sampling rate. A disk with a small indentation, mounted on the surface of the monitor case 140 mm closer to the P than the fixation point, served as the starting point for the stylus at the beginning of each trial.

Design

Each P ran for five sessions each lasting about one hour. The first of these was treated as practice. In it the Ps were exposed to all of the experimental manipulations.

This experiment had one between-participants factor, typing skill, and seven within-participants factors. There were either two or four dependent variables, depending on the response condition. In the keypress condition, the two dependent variables recorded were reaction time – i.e., the time from stimulus onset until a response key was registered – and an identifier for the response key that was pressed. In the touching condition, the four dependent variables were: (1) reaction time, the time from stimulus onset until the onset of a touching movement was detected, (2) duration, that is, the time from movement onset until the end of the movement was detected, (3) end point error, that is, the distance between the movement and the center of the target circle, and (4) response error, which coded whether or not the movement ended outside of the target circle and several other error conditions that could occur.

Three of the within-participant factors varied from trial to trial: (1) stimulus position, one of N_A possible locations for that block, (2) repetition, that is whether the stimulus/response for a trial matched that of the previous trial, and (3) cue onset delay. Two of the within-participant factors were fixed within a block but varied across blocks within a test session: (4) number of possible targets N_A, two or 6, and (5) stimulus arrangement. The last two factors, (6) response-mode (keypress or touching) and (7) type of indicator-stimulus (spatial or symbolic), were both fixed within all blocks of a test session but varied across test sessions, with one of the four combinations of these two variables occurring on each of the four test days. Their order was balanced across sets of Ps using digram-balanced Latin squares.

Figure 2 shows the spatial arrangement of the fixation, the eight possible spatial indicator stimuli, the touching response targets, and the mapping of the symbolic indicator stimuli on to these locations. In the symbolic indicator stimulus conditions, the indicator stimulus was always presented at the same location as the fixation. The subsets of the eight locations used in a block were constrained to include equal numbers of locations to the right and left of the vertical axis of symmetry. Due to this constraint, there are exactly 16 ways of selecting sets of either two or six locations. Each of these stimulus arrangements was used once in the 32 test blocks. A session was composed of 36 blocks, 4 practice blocks followed by the 32 test blocks alternating between N=2 and N=6 blocks. Each block consisted of 18 error-free trials with two catch trials included to help eliminate anticipatory movements.

Since the touching response tasks all involve extended movements of a single effector, Ps might be tempted to initiate the movement before the indicator stimulus appeared. In order to minimize the possibility of such anticipations, the cue onset time varied randomly from trial to trial according to a truncated, discrete approximation to an exponential distribution. The bins of this distribution separated by 16.67 ms. It ranged from 100 ms before to 350 ms after the point in time when the stimulus would normally have been expected given the fixation sequence (see details below).

Procedures

Procedures for Touching-Response Sessions. Due to differences in height and position relative to the computer monitor across Ps, each session began with a calibration procedure in which the OptoTrak coordinates of the stylus were determined for perceived locations on the display screen. Each P touched the stylus to the center of nine squares displayed in an array, each with known pixel values. From these data, a linear transformation was estimated that mapped the screen coordinates into the three- dimensional coordinate system of the OptoTrak. At the end of this calibration process, the Ps checked to be sure that the registration was accurate before beginning each block.

Each trial began with the screen blank except for a message to move the cursor to the starting location, which was a point on the screen case just below the fixation. After the stylus had remained within 3 mm of the starting location for 250 ms, this message disappeared, and a subset of two or six out of the eight possible white circles, appeared, one at each of the possible target positions determined by the stimulus arrangement in use for the block. At this point, the fixation display sequence also began. The fixation cross blinked on 500 ms and off 500 ms for two cycles; this both directed visual attention to the fixation point and set up a temporal expectation of the target. The randomly selected stimulus onset time C was drawn from a distribution constructed so that the mean stimulus onset time coincided with the time T when the flashing fixation sequence would have begun its third cycle. If the stylus was lifted away from the starting location at any time before T-150 ms, an error message was presented and the trial was restarted. If the stylus moved out of the starting area before C+100 ms, or, for a catch trial, any time up to T+500 ms, the movement was labeled an anticipation error, an error message was displayed and a new trial was randomly selected.

The factor type-of-indicator-stimulus had two levels. In the spatial-indicator-stimulus condition the indicator-stimulus was a change that occurred at the location of the target: the dark inside of one of the potential target circles was filled in to match the white outline of the circle. In this condition, the P was instructed to move the stylus quickly to a point within that circle. In the symbolic-indicator-stimulus condition, the indicator stimulus was a 1.5 cm tall letter presented at fixation. In this condition, the P was instructed to move the stylus quickly to a point within the circle that was associated with the letter.

The instructions, like those of a discrete Fitts task, emphasized minimizing the total time to complete the movement, and treated all movements ending within the target circle as correct, while all movements ending outside the target circle were labeled errors (Fitts, 1954). The movement was determined to have begun when the stylus moved more than 3 mm in any direction from the starting location. The movement was determined to have ended when the stylus came within 2 mm of the surface of the display. (The calibration procedure estimated the curvature of the display surface and this curvature was taken into account when determining the end of the movement.) Movement trajectory data were retained starting 500 ms before the target cue onset and ending 500 ms after the movement was determined to have ended.

Procedures for Keypress Sessions. The keypress task was indistinguishable from the touching task in timing, stimulus arrangement and presentation. Additionally, the feedback was identical for both bonuses and target scores, which are both fully described below. The primary difference in keypress-task sessions was that, in response to the indicator-stimulus, Ps were to depress a key on a standard computer keyboard rather than use the stylus to respond with a single, aimed, touching arm movement.

The keys used were on the home-row: ‘A’, ‘S’, ‘D’, ‘F’ was used for the left hand, and the keys ‘J’, ‘K’, ‘L’, ‘;’ were used for the right hand responses. These were also the characters used as indicator stimuli in the symbolic-indicator-stimulus conditions. At the start of each trial, the P positioned the fingers of the two hands on or just above these keys. Because the extent of the movement required to press a key was minimal, movement trajectories were not collected, the responses were registered based solely on the actuations of the keys, and the Optotrak calibration was not done.

The mapping of response finger/keys onto the eight possible stimulus locations was fixed within and across Ps. Because the combination of possible target locations used as stimuli varied from block to block, the finger/key combinations used to make responses also changed from block to block. In the N = 2 condition, in which only one finger on each hand was used to make responses, there was little tendency to be confused about the finger/key required to respond to the stimulus on any given trial. However, in the N = 6 condition, initially associating each stimulus in the set with the finger/key with which to respond sometimes posed a challenge. To help Ps overcome this challenge, at the start of each block, the set of target locations for that block was displayed. Then, in turn, each target location was highlighted and the letter on the keyboard, which was associated with the key that was the response for that target, was displayed until the appropriate key was pressed.

The instructions emphasized that all eight of the P’s fingers should be on the appropriate response keys at the start of each trial, even in the N = 2 blocks. An experimenter monitored the P’s responses to ensure that these instructions were followed.

Feedback and Bonuses in Both Session Types

After each touching or keypress response, a message was displayed giving the movement time in hundredths of a second. In addition, after a touching response, a small marker was displayed at the location on the screen determined to be the movement endpoint. If the wrong key was pressed or if the touching-movement endpoint was outside of the target region, the message ‘‘MISSED TARGET’’ was also displayed. This feedback stayed on the screen for 2 s. At the end of this period the display was cleared and a new trial began.

After the last trial in each block, the display was cleared and a message was presented summarizing for the P his/her performance and providing a score for the block. In addition to the score, this summary included the average total movement time, in hundredths of a second, the count of the number of errors—i.e., trials on which the movement missed the target—and the count of the number of anticipation errors. The score was calculated as the sum of the average total movement time (in hundredths of a second; typically, about 40 in the keypress task and 55 in the touching task), three points for each missed target and five points for each anticipation error. The P received a bonus of $.05 for each block for which the score was less than or equal to a target score for that block. The bonuses were designed to reward good performance. Four separate target scores were maintained for each P reflecting the four combinations of the two response conditions and the two levels of N. At the end of each block, the appropriate one of these scores was adjusted based on the average score for that block. Let T_i be the target score for block i and S_i the average score for that block. T_1 was always set to 100, a value larger than the expected score for the first block of any condition. Subsequent target scores were computed according to a recursive formula.

$$T_{i+1} = \begin{cases} T_i - 0.67\,(T_i - S) & \text{if } T_i \geq S_i \\ T_i - 0.25\,(T_i - S) & \text{if } T_i < S_i \end{cases}$$

Post Processing of Movement Trajectories

For subsequent analyses of the trajectories, the raw trajectories were first fit using a smoothing spline, computed to maintain a tolerance of 0.5 mm between the measured and smoothed values, and temporally re-sampled to have 21 points. Thus, the interval between pairs of the re-sampled trajectory points corresponded to 5% of the duration of the original movement trajectory.

Results

Typing Speed

The novice typists had raw typing scores between 29 and 49 words per minutes (*M* = 41, *SD* = 6). The expert typists had raw typing scores between 71 and 112 words per minutes (*M* = 89, *SD* = 13).

Data Collection Errors

There were two kinds of errors. Here we summarize errors that occurred because of equipment failure or because the data collected were suspect in some way. In a subsequent section, we turn to errors in which an incorrect response was produced.

Across all 16 Ps, there were 179 trials in the keypress response condition (1.25%) and 62 trials in the touching response condition (0.44%) that had to be discarded and rerun within the same block because of problems recording the data: e.g., in the keypress condition, multiple keys were pressed “simultaneously” or a key was pressed that was not one of the possible responses; in the touching condition, the Optotrak was unable to track fully the stylus emitter. In the touching condition, the frequency of occurrence of these errors was almost identical for the novice and expert Ps; however, in the keypress condition there were significantly more of these errors for the expert typists (1.48% versus 1.02%, $\chi^2(1) = 6.105$, $p = .013$).

There were few anticipation errors, that is movements made on a catch trial or movements that began within 100 ms of the stimulus onset on a normal trial: this happened on 4 trials in the keypress condition and on 43 trials (0.30%) in the touching response condition. This suggests that the inclusion of catch trials successfully induced the Ps to wait for the cue stimulus before initiating a response. These trials were detected as they happened, discarded and rerun within the same block.

Once the experiment was complete, separate analyses were done for the keypress and touching conditions to identify trials with unusually long or short latencies relative to the distribution of each subject. To make the latency distributions more symmetric, this analysis was done after taking logarithms. A trial was flagged as unusually short or long if it was more than three times the inter-quartile range away from the median. This analysis identified no trials having suspiciously short latencies in the keypress condition and 8 trials (0.06%) in the touching

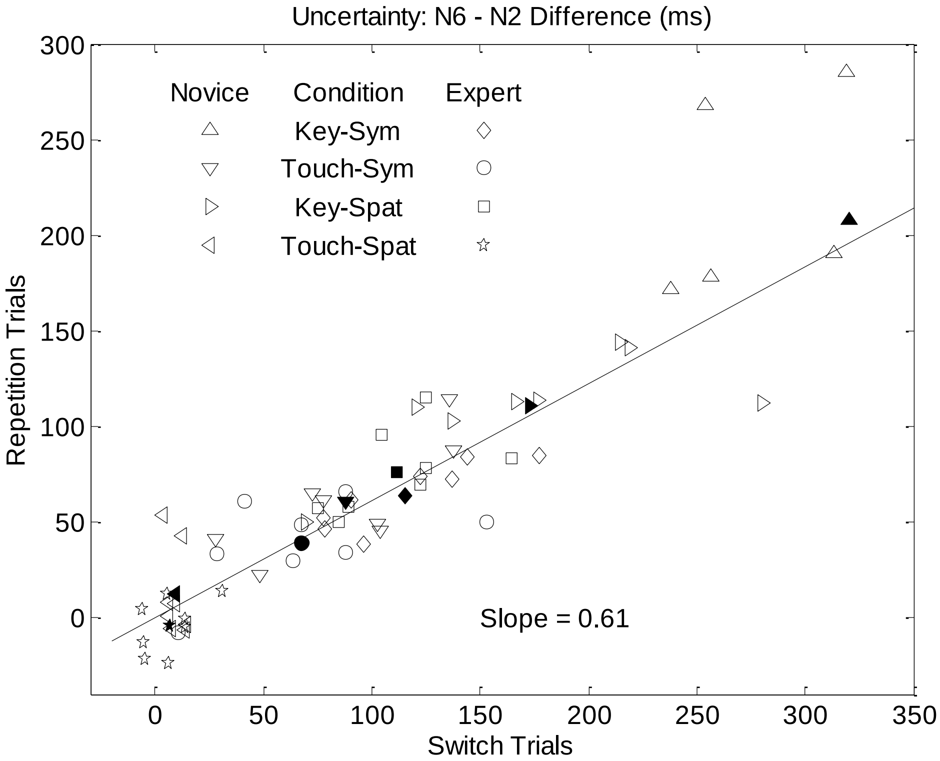

Figure 3: Scatter plot of the uncertainty effect on repetition versus switch trials. Each open plotting symbol represents the results of one participant in one of the four tasks, as shown in the legend. The filled plotting symbols represent the data averaged over participants. The solid line is the best fit to the average data constrained to pass through the origin.

condition. In addition, this analysis identified as having suspiciously long latencies 34 trials (0.24%) in the keypress condition and 27 trials (0.19%) in the touching condition. The data from these trials was discarded, and, because they could only be identified after the subject running was complete, they were not rerun. Excluding these trials from the analysis did not change the direction on any of the reported effects, but it did result in lower levels of residual error.

Reaction Time

Repetitions. Taken together, Equations (5) and (6) suggest a specific form for the repetition effect: for a task, the uncertainty difference for repetition trials should be a fixed proportion of the uncertainty for switch trials. To explore this strong prediction, Figure 3 is a scatter plot with the uncertainty effect for repetition trials, on the vertical axis, and the uncertainty effect for switch trials, on the horizontal axis. The 64 open symbols represent the results for all of the 16 Ps with different plotting symbols used to mark each of the four combinations of indicator stimulus and response mode. The eight filled symbols indicate the average across Ps within typing skill groups. If the hypothesis, stated in the Introduction, is correct that detecting a repetition allows both S-R mapping and effector selection processes to be bypassed, the average data points as well as those from each P should fall on a line with a slope equal to $(1 - p_{Check})$.

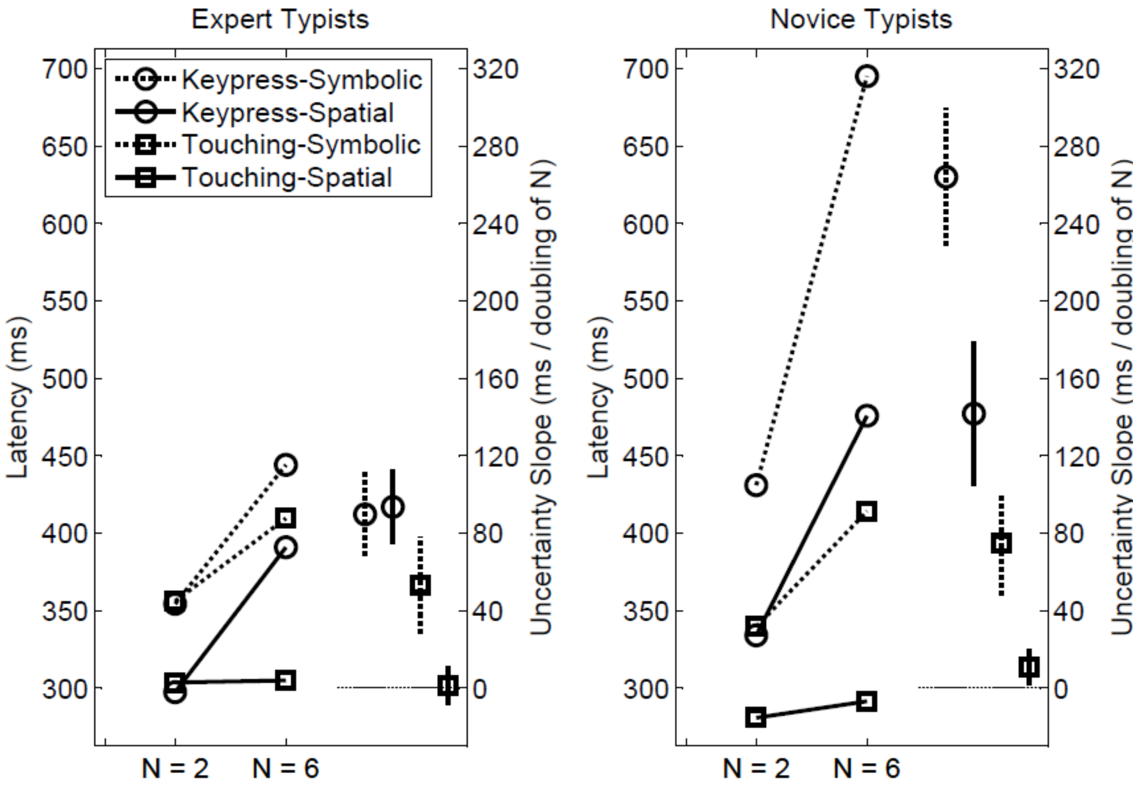

Figure 4: Summary of the Mean Reaction Times and Uncertainty Effects on Switch Trials. The panels show the reaction time data for the two typing skill groups, broken out by the four combinations of indicator stimulus and response, as indicated in the legend. Plotted on the left side of each panel, and using the vertical scale on the left, are the mean reaction times for both levels of N_A. Plotted on the right side of each panel, and using the vertical scale on the right, are the uncertainty slope estimates for each task type. The error bars represent 95%-confidence intervals.

This appears to be true. However, nothing in this model requires the slope, $(1 - p_{Check})$, to be constant across Ps although this also appears to the case. Thus, all 64 data points in this scatter plot fall close to a straight line constrained to pass through the origin. The slope of this line suggests that the size of the uncertainty effect on repetition trials is approximately 0.64 (0.61↔0.68)ii of that on switch trials within condition. For the data averaged across subjects within typing-skill groups, the eight filled symbols in Figure 3, the proportional relationship describes 99.1% of the variance; even for the data broken out by Ps, the open circles in the figure, this relationship still describes 77% of the variance.

Data Summary. The reaction time data from the switch trials, collapsed over Ps within each typing-skill group and three other variables, stimulus configuration, target location, and cue onset delay, are summarized in Figure 4. The two panels of this figure separately display the data for the novice and expert typists. The horizontal axis breaks out the data by the two levels of N_A, and for the keypress response conditions, the two, confounded levels of N_E. The different combinations of line types and plotting symbols in each panel identify the data from the four combinations of the indicator stimulus and the response type factors. The right side of each panel shows the uncertainty effect slopes for each of the four conditions. These slopes are computed as $U_{Switch}/\log_2(3)$, where U_{Switch} is the contrast defined in Equation 5; these slopes may be interpreted as the reaction time increase associated with each doubling of N_A. Because Figure 4 includes only data from the switch trials, these estimates are not inflated by the unequal occurrence of repetitions across levels of N_A. The downside is that the confidence intervals on these estimates are somewhat larger, since they include fewer data points. For completeness, Table 2, includes the means for both the repetitions and the switch trials.

Model Fit. To understand the reaction time data, it is useful to focus on parameter estimates derived from the fit of a descriptive model based on Equations (3) and (4). The nine parameters of this model are identified and described in Table 3. For the seven of these parameters that describe the effects of N_A, indicator stimulus type, or response method, for clarity, the table also includes the design matrix coefficients associated with these factors.

This nine-parameter model was fit separately to the 16 means for each P obtained by collapsing over stimulus arrangement, stimulus position, and cue onset delay. Not surprisingly, the fits were good: for the novice typists, ω^2 ranges from .93 to .98; for the expert typists, for whom the effect sizes are smaller, ω^2 for one P was .84 and for the other seven it ranged from .91 to .95. Keep in mind, however, that the primary purpose of this model is to provide a more meaningful decomposition of the data.

Table 2: Reaction time averaged over Ps within skill groups broken out by skill level (novice or expert), response mode (keypress or touching), indicator stimulus (symbolic or spatial), $\boldsymbol{N_A}$ (2 or 6), and repetition (switch or repeat). Also included for each combination of skill level, response mode, and indicator stimulus are the main effects of $\boldsymbol{N_A}$ and repetition along with their interaction.

			$N_A = 2$		$N_A = 6$		Effects					
							N_A		Repetition		Interaction	
		Repeat =	No	Yes	No	Yes	Mean	SE	Mean	SE	Mean	SE
Novice	Keypress	Symbolic	424.6	431.3	707.1	599.1	225.1	12.1	50.7	17.3	114.7	29.1
		Spatial	324.5	343.5	494.0	454.0	140.0	15.1	10.5	5.6	59.0	15.8
	Touching	Symbolic	336.8	342.9	425.0	403.9	74.6	11.6	7.5	4.4	27.2	8.8
		Spatial	280.0	281.7	289.2	293.5	10.5	3.9	-3.0	3.2	-2.6	8.7
Expert	Keypress	Symbolic	349.6	359.2	465.5	421.6	89.2	9.4	17.1	4.6	53.6	7.8
		Spatial	289.3	305.4	400.6	381.6	93.7	8.0	1.4	4.0	35.0	8.7
	Touching	Symbolic	357.0	355.4	424.8	394.8	53.7	10.5	15.8	7.2	28.4	13.3
		Spatial	304.3	303.0	310.9	299.5	1.6	4.1	6.4	2.1	10.1	4.7

Table 3: Parameters included in the 9-parameter model fit to the data from each P.

		$N_A = 2$				$N_A = 6$			
		Touching		Keypress		Touching		Keypress	
Parameter	Description	Spatial	Symbolic	Spatial	Symbolic	Spatial	Symbolic	Spatial	Symbolic
t_{Add}^{SpatPt}	Additive component for touching response with a spatial indicator stimulus	1	1	1	1	1	1	1	1
t_{Add}^{Key}	Additive increment for keypress response	0	0	1	1	0	0	1	1
t_{Add}^{Sym}	Additive increment with a symbolic indicator stimulus	0	1	0	1	0	1	0	1
b_{ES}^{Key}	Slope of the increase due to effector selection	0	0	$\log_2(2)$	$\log_2(2)$	0	0	$\log_2(6)$	$\log_2(6)$
b_{SR}^{Spat}	Slope of the increase due to S-R mapping with a spatial indicator stimulus	$\log_2(2)$	0	$\log_2(2)$	0	$\log_2(6)$	0	$\log_2(6)$	0
$b_{SR}^{SymTouch}$	Slope of the increase due to S-R mapping for touching responses with a symbolic indicator stimulus	0	$\log_2(2)$	0	0	0	$\log_2(6)$	0	0
b_{SR}^{SymKey}	Slope of the increase due to S-R mapping for keypress responses with a symbolic indicator stimulus	0	0	0	$\log_2(2)$	0	0	0	$\log_2(6)$
p_{check}	Probability of checking for a repetition								
t_{check}	Time required to check for a repetition								

Table 4 summarizes the resulting parameter estimates. In looking at this summary, we will focus first on the five predictions made at the end of the Introduction. Consistent with the first prediction, b_{ES}^{Key}, the component of the uncertainty effect associated with effector selection, is relatively large compared with uncertainty effects in choice reaction time tasks for Ps at both levels of typing skill: 90.6 ms per doubling of effectors for novice typists and 51.3 ms per doubling for expert typists. The difference between these estimates is consistent with the second prediction; the between-groups test results suggest that there is moderate evidence that the contribution of effector selection to the uncertainty effect is larger for novice than for expert typists. Consistent with the third prediction, the estimates of b_{SR}^{Spat}, the increase in reaction time associated with the S-R mapping of spatial indicator stimuli, are relatively small compared with standard uncertainty effects, 4.7 ms per doubling for novice typists and 6.7 ms per doubling for expert typists. Although there is weak evidence that this component of the uncertainty effect may be non-zero for expert typists, there is little evidence to support a difference between the two groups. Consistent with the fourth prediction there is very strong evidence that $b_{SR}^{SymTouch}$, the estimate of the S-R mapping cost for symbolic indicator stimuli and touching responses, is non-zero for both groups, but little evidence that this cost is different for the two groups. There is also strong evidence that b_{SR}^{SymKey}, the estimate of the S-R mapping cost for symbolic indicator stimuli and keypress responses, is non-zero for both groups, consistent with the fifth prediction. However, by contrast with $b_{SR}^{SymTouch}$, but also consistent with the fifth prediction, there is evidence that this slope is reliably larger for novices, 92.6 ms per doubling, than for experts, 15.6 ms per doubling, as would be expected given the additional practice that expert typists have had with touch typing.

Consistent with the earlier analysis of repetition effects, the parameter estimates, p_{check} and t_{check}, are stable across Ps and between the two groups. The estimate of the time required to perform this check, roughly 50 ms, is quite stable across Ps and groups. This estimate is also close to that assumed in the model fitting done by Schneider and Anderson (2011, Table 1).

Although the parameters t_{Add}^{SpatPt}, t_{Add}^{Key} and t_{Add}^{Sym} are needed to fit the model, they are otherwise of little interest to us. It suffices to note that there is no evidence that they differ for novice versus expert typists.

Table 4: Parameter estimates resulting from the 9-parameter model fit.

		t_{Add}^{SpatPt}	t_{Add}^{Key}	t_{Add}^{Sym}	b_{ES}^{Key}	b_{SR}^{Spat}	$b_{SR}^{SymTouch}$	b_{SR}^{SymKey}	p_{check}	t_{check}
Novice Typists	1	268.4	-50.3	-5.1	135.7	4.6	45.0	35.7	0.178	49.2
	2	292.9	50.9	116.6	37.9	28.3	61.9	138.4	0.020	72.6
	3	285.9	48.6	17.9	98.2	1.2	60.4	112.8	0.466	53.3
	4	293.2	-135.4	-1.7	102.7	0.4	30.8	48.5	0.235	57.5
	5	272.9	-22.6	-18.0	110.2	6.2	77.6	117.3	0.166	37.1
	6	269.3	-61.8	5.6	119.8	-2.0	51.8	66.6	0.004	55.9
	7	241.3	-50.5	30.2	70.0	2.9	44.7	72.2	0.135	50.8
	8	237.4	-21.5	-25.2	50.7	-4.0	30.6	149.6	0.132	50.3
	Mean	270.2	-30.3	15.0	90.6	4.7	50.3	92.6	0.167	53.3
	SD	21.4	60.7	44.8	34.4	10.1	16.1	42.5	0.144	9.9
95% Interval	Upper	288.1	20.4	52.5	119.4	13.1	63.8	128.2	0.287	61.6
	Lower	252.2	-81.1	-22.4	61.9	-3.8	36.9	57.1	0.047	45.0
	t	35.647	-1.413	0.949	7.459	1.312	8.851	6.163	3.287	15.207
	p	0.000	0.201	0.374	0.000	0.231	0.000	0.000	0.013	0.000
Bayes Factor		>1000	0.71	.48	204	.65	509	77.5	5.20	>1000
Expert Typists	1	299.2	-21.1	44.5	71.1	5.5	19.1	2.6	0.109	47.5
	2	321.2	-50.7	44.2	60.0	18.8	76.4	19.7	0.199	49.2
	3	254.4	-29.2	12.0	30.1	9.9	46.4	24.1	0.082	47.8
	4	269.7	-54.4	61.9	50.9	7.3	25.8	4.9	0.186	46.0
	5	297.6	-54.9	52.6	45.9	14.2	26.7	29.5	0.148	47.9
	6	269.5	-39.2	36.1	37.9	1.5	41.2	10.0	0.212	46.6
	7	331.1	-56.3	-0.2	55.0	-5.6	39.9	38.7	0.206	50.6
	8	223.4	-21.7	49.0	59.6	2.3	-5.7	-4.8	0.235	49.2
	Mean	283.3	-40.9	37.5	51.3	6.7	33.7	15.6	0.172	48.1
	SD	35.8	15.2	21.1	13.1	7.7	23.8	14.9	0.054	1.5
95% Interval	Upper	313.2	-28.3	55.2	62.3	13.2	53.6	28.0	0.217	49.4
	Lower	253.3	-53.6	19.9	40.3	0.3	13.9	3.1	0.127	46.8
	t	22.369	-7.629	5.025	11.059	2.488	4.013	2.959	8.996	89.633
	p	0.000	0.000	0.002	0.000	0.042	0.005	0.021	0.000	0.000
Bayes Factor		>1000	230	29.3	>1000	2.17	11.1	3.65	555	>1000

Novice - Expert		t_{Add}^{SpatPt}	t_{Add}^{Key}	t_{Add}^{Sym}	b_{ES}^{Key}	b_{SR}^{Spat}	$b_{SR}^{SymTouch}$	b_{SR}^{SymKey}	p_{check}	t_{check}
	Diff	-13.1	10.6	-22.5	39.3	-2.1	16.6	77.1	-0.005	5.2
	SD	21.4	35.8	60.7	9.9	0.1	0.1	21.1	15.180	44.8
95% Interval	Upper	19.2	61.8	16.5	68.8	7.6	38.7	113.3	0.118	13.6
	Lower	-45.4	-40.5	-61.5	9.9	-11.7	-5.4	40.8	-0.128	-3.1
	t	-0.889	0.480	-1.285	3.024	-0.462	1.639	4.839	-0.094	1.476
	P	0.392	0.644	0.228	0.014	0.652	0.127	0.001	0.927	0.182
	df*	11.444	7.872	9.967	8.998	13.070	12.302	8.690	8.946	7.328
Bayes Factor		.46	.37	.63	3.92	.37	.88	24.7	.34	.75

* Non-integral degrees of freedom result from the use of a standard procedure for these comparisons that does not assume homogeneity of variance (Maxwell & Delaney, 1990, pp. 165-168). The degrees of freedom for all of these *t*-statistics would be 14, if the assumption of homogeneity were appropriate.

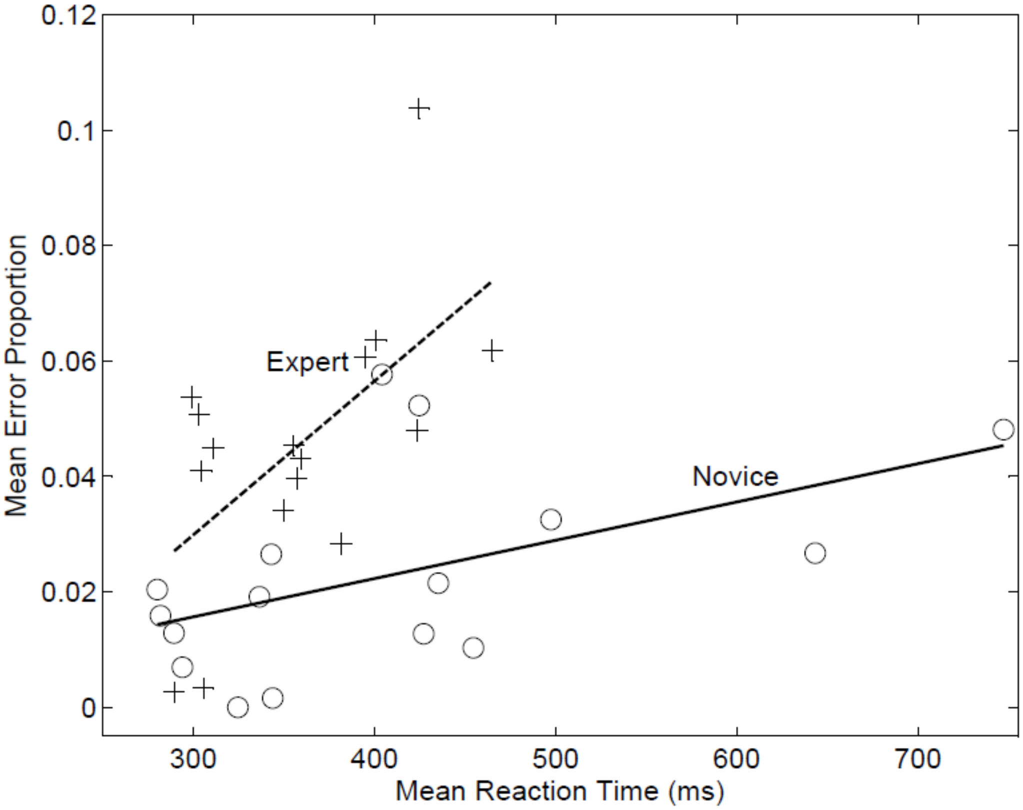

Figure 5: Scatter plot showing the relation between the mean proportion of errors and the mean reaction time. Each plotting symbol represents data from one participant in one of the four tasks. The open circles are data from the novice typists; the solid line is the best linear fit. The crosses are data from the expert typists; the dashed line is the best linear fit.

Response Errors

In the touching response condition, a trial was classified as an error when the movement ended outside of the target circle. Trials in the keypress response condition were classified as errors when an incorrect key from the possible response set was pressed. Overall, the average error rate was low, 3.4% (SE = 0.5%). However, this average masks substantial variation in the error rates across conditions and subject groups. Viewed in isolation, this variation, like that for reaction time, appears complex. However, Figure 5 shows that much of this complexity can be understood in terms of two associations. In general, there are more errors in conditions that have longer reaction times – i.e., difficult S-R mapping and/or effector selection leads to slower reaction times and more errors. In addition, however, this relationship is stronger for expert than for novice typists – i.e., for conditions leading to roughly the same mean reaction time, expert typists produced more response errors than novice typists, perhaps reflecting a speed-accuracy tradeoff.

Other Measures of Performance for Touching Responses

Touching responses differ from keypress responses in having a measurable movement trajectory that evolves over a period of time, a duration, and a movement endpoint that can be treated quantitatively as well and qualitatively – with a keypress response the target key is either pressed correctly or it is not.

The mean duration for the touching responses was 379 ms (95% confidence interval: 336↔422). The duration data were analyzed using a four factor, mixed ANOVA. The three within-participants factors were N_A, repetition, indicator stimulus. Skill level was the lone between-participants factor. This analysis revealed that touching movement duration increased for trials with larger N_A, *F*(1,14) = 16.271, *p* = .001, BF = 35.7, and for trials with a symbolic indicator stimulus, *F*(1,14) = 10.106, *p* = .007, BF = 8.12. These main effects were made more complex by an interaction, *F*(1,14) = 10.219, *p* = .006, BF = 8.36. The nature of this interaction was that the uncertainty effect was small, 4.6 ms, but just statistically reliable for the spatial indicator stimulus (0.1↔9). By contrast, there was a large, statistically significant uncertainty effect for the symbolic indicator stimulus, 44 ms (18↔70).

The average endpoint error, the distance between a target center and the point at the end of a movement to a target, was 2.8 mm. Unlike movement durations, endpoint error did not vary systematically or substantially across conditions.

Finally, the existence of duration differences suggests the possibility that Ps may have begun the touching movement before the target was fully identified. Past reports in this sequence (Wright et al., 2007 & 2011) have reported extensively an analysis of the movement trajectories designed to explore this possibility. The same analysis was conducted for these data. However, in the interest of space, this analysis will not be reported here in detail since the outcome was the same: i.e., at 10% of the movement duration (roughly 38 ms after movement was initiated) it was possible to correctly classify the eventual target of over 80% of the movements and this percentage grows rapidly as the movement continues to evolve.

Discussion

The primary purpose of this experiment was to explore the possibility that effector selection is the source of a large part of the uncertainty effect that has traditionally been ascribed to S-R mapping in choice reaction time tasks. The results strongly support this hypothesis. The data are well fit by a model built on the assumption that effector-selection adds nothing to reaction time in the conditions for which there is a single, known effector, the touching responses, but provides a substantial component of the uncertainty effect in the conditions with keypress responses, in which each possible response involves a different finger. For less skilled typists, Ps who were observed to use just two or three fingers when copy typing, effector selection is estimated to increase reaction time by 90.6 ms per doubling of the number of effector alternatives. Not surprisingly, the effector-selection cost for keypress responses was estimated to be smaller for skilled, touch typists: 51.3 ms per doubling.

This result is important for two reasons. It highlights the importance of effector selection in immediate behaviors, such as choice reactions, a factor that has been largely overlooked in much of the previous research on Hick's law. In addition, recognizing and accounting for the contributions of effector selection to overall uncertainty effects can lead to better estimates of the size of the S-R mapping contribution. Specifically, our results show that the S-R mapping of spatial locations onto consistent response locations, whether with a touching response or a keypress response, is associated with little or no increase in reaction time. Based on the data from this experiment, the best estimate for this component of the uncertainty effect is only about 6 ms per doubling of the number of S-R alternatives. Together, these insights can provide a principled explanation for why the overall effect of uncertainty is quite small, if not zero, in some conditions. As suggested by Wright et al. (2011), small uncertainty effects should result when S-R compatibility is high and the effector to be used to make the response is known in advance.

Switching perspective, the results nicely isolate the effects of a particular form of practice, experience with touch-typing. The parameter estimates in Table 4 suggest that, in a choice reaction time task, skilled typists differ from novice typists in just two areas: there was moderate evidence that skilled typists can select more quickly which of several fingers is the movement effector (b_{ES}^{Key}) and strong evidence that they more quickly map individual letters onto the appropriate keypress responses (b_{SR}^{SymKey}). For the other seven components of the descriptive model, there is not good evidence for a difference between the two skill groups. Thus, as can be seen in Figure 4 and Table 2, although the expert typists clearly respond faster in the tasks with keypress responses, especially when these were combined with a symbolic stimulus, if anything the novice typists were faster to respond in tasks involving touching responses.

The top panel of Figure 6 contains a scatterplot of the estimates b_{ES}^{Key} and b_{SR}^{SymKey}, the two parameters that changed with practice. The relationship between the task components in this scatterplot reveals additional detail about how expertise functions in this task. First, there is a clear separation between the novice and expert groups in this bivariate space, even though there is overlap of the groups in each dimension considered separately. This pattern, in turn, reflects a possible negative correlation between the estimates of these two parameters for both groups (novices: *r* = -.73 [-.95↔ -.05]; experts: *r* = -.35 [-.86 ↔ .47]). If these small sample correlations reflect a true negative association, this would suggest an intriguing interdependence in the skills required by this task. A second point revealed in these data is that, while improvement is clearly possible in both parameters, it appears to be more difficult to eliminate the component of the uncertainty effect due to effector selection than that due to S-R mapping. As shown in Table 4, three of the Ps in the expert group had estimates of b_{SR}^{SymKey} that were close to zero and the mean for all 8 was only 15.6 ms per doubling. By contrast the smallest estimated value of b_{SR}^{SymKey} observed in the expert group was 30 ms per doubling and the mean was 51.3 ms per doubling. Put another way, although S-R mapping was a major contributor to the uncertainty effect for novice typists, for those Ps who were expert typists, most of the uncertainty effect is due to effector selection.

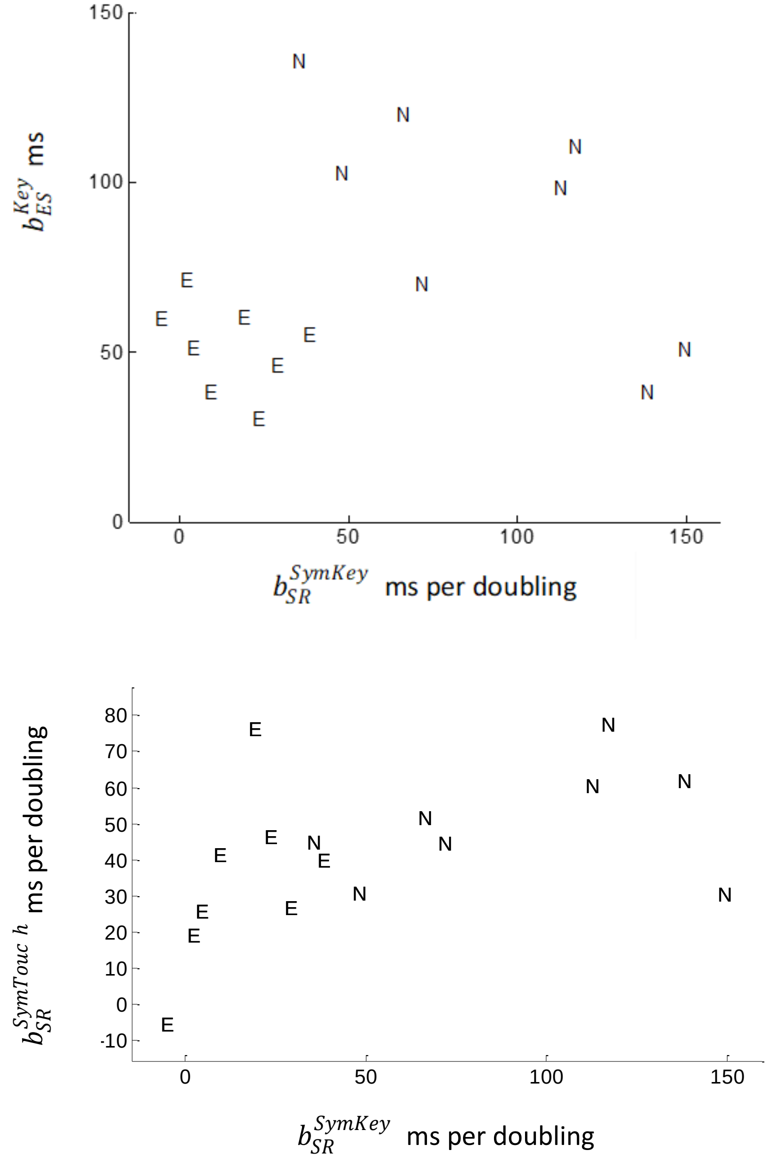

Figure 6: **Scatter plots showing the different ways that typing expertise is reflected in the parameter estimates from Experiment 1 (Table 4).**

In both panels, data points marked with E are for Ps in the expert typist group and those marked with N are for Ps in the novice group. The horizontal axis in both panels is the estimates of b_{SR}^{SymKey}, the slope parameter estimating the slowing due to S-R mapping in tasks with symbolic stimuli and keypress responses. The top panel shows the relationship between this parameter and b_{ES}^{Key}, the slope parameter estimating the slowing due to effector selection. The bottom panel shows the relationship between b_{SR}^{SymKey} and $b_{SR}^{SymTouch}$, the slope parameter estimating the slowing due to S-R mapping in tasks with symbolic stimuli and touching responses.

Another interesting aspect of these data, although one that is somewhat peripheral to the main questions of this paper, involves the estimates for the parameters b_{SR}^{SymKey} and $b_{SR}^{SymTouch}$ which are shown in the scatterplot in the bottom panel of Figure 6 broken out by skill group. These slope parameters summarize the reaction time increase due to S-R mapping of symbolic indicator stimuli for each of the two response conditions. Consistent with Prediction 4 in the Introduction, S-R mapping contributed substantially to the uncertainty effect when a symbolic indicator stimulus was paired with a touching response. The size of this increase was similar for novice (50.3ms per doubling) and expert typists (37.3ms per doubling). Consistent with Prediction 5, S-R mapping also contributed to the uncertainty effect when the symbolic indicator stimulus was paired with a keypress response; however, in this case, the increase for novice typists (92.6ms per doubling) was substantially larger than for expert typists (15.6 ms per doubling). The data provide strong support for this interaction [$t(10.22) = 3.796$, $p = .003$, BF = 17.35]. These data are of interest because they may shed some light on the nature of the S-R mapping process. In both cases, the "S" of the S-R mapping is the same, a letter serving as a symbolic indicator; what, however, is the "R"? If effector selection is, as we hypothesize, done by a separate process (along with, presumably, specifying the other details that are effector-dependent but required by the motor system to act on the chosen spatial location), then one plausible answer is that the response specification is abstract, specifying only, for example, the spatial location to be acted on. However, if this surmise were correct, it would make sense to expect that, for any specific P, the estimates for $b_{SR}^{SymTouch}$ and b_{SR}^{SymKey} should be similar. Although there appears to be a positive correlation between the estimates for these two coefficients across Ps ($r = .50$ [.01 ↔ .80]), there are big, within-P differences between these estimates, especially for the novice typists.

We can imagine two plausible resolutions to this puzzle. For the first, we note that the to-be-acted-on locations associated with the two response types have at least one important difference: for touching responses they are visible locations on the screen but for typing responses they are nonvisible locations on the keyboard. It is possible that the response code for mapping a symbolic stimulus to a visible location is different from that for mapping a symbolic stimulus to a nonvisible location and that experience with touch typing substantially decreases the difficulty of this second mapping process. A second explanation proposes that the response code that results from the S-R mapping process includes not only the to-be-acted-on location but also an abstract specification of the to-be-performed action: e.g., *touch* versus *keypress*. In this case also, it is possible that touch typing experience might differentially reduce the time required to accomplish this mapping when the to-be-performed action is a keypress.

The analysis of the data reported here depended heavily on the treatment of the repetition effect suggested by Schneider and Anderson (2011). The success of our modelling provides additional evidence supporting this approach. In addition, our results both add new insights and raise additional questions about repetitions. The summary in Figure 3 and the more precise estimates in Table 4, support not only the proposal of Schneider and Anderson that the repetition of S-R pairs allows a probabilistic skipping of the S-R mapping process but also the suggestion built into our model that detecting repetitions also allows skipping the effector selection process. Figure 3 illustrates the insight from this model that was important to developing a fuller understanding of the data from this experiment: that the size of the repetition effect in a condition is proportional to that of the uncertainty effect in that condition. What seems particularly amazing about this result is that, at least within the context of this experiment, the probability of looking for a repetition (roughly .17) and the time that this checking takes (close to 50 ms) are both remarkably stable across Ps and conditions. The value of t_{check} estimated here is essentially identical to the fixed value (this was not a free parameter in their model fits) chosen by Schneider and Anderson (2011) because it is the default time for firing a production in the Act-R model. The aspect of our data suggesting that there is still more to understand about repetitions is that, as shown in Table 2, when $N_A = 2$, the mean reaction time for the switch trials, rather than being longer, was shorter than that for the repeat trials especially with keypress responses (keypress = -13.2 ms [-22.6 -3.9]; touching = -1.3 [-5.4 2.7]). We have observed this pattern in our previous research (Wright et al., 2007 and 2011) and it has been reported by others (e.g., Schneider and Anderson, 2011, Experiment 1). As Schneider and Anderson (2011) have noted, the case with $N_A = 2$ is special since, if a stimulus switch is detected, the P can simply assume that the other stimulus is present.

It is unfortunate that this experiment did not include more levels of N_A. As Kornblum (1967) noted and discussed above, repetitions in the case with $N_A = 2$ may be unusual. Also, including more levels of N_A would also have allowed us to fit a somewhat richer model. However, when this experiment was being planned, the goal was to look for the factors that led to observed uncertainty effects that are close to zero as opposed to the much larger effects typically observed. For that purpose, an elaboration of the design, which we had used previously (Wright et al., 2007 and 2011), that, by including just two levels of N_A, allows careful balancing of the stimulus conditions, seemed appropriate. Also, the five-day time commitment required of Ps just for this design already was making it difficult to recruit Ps. The next experiment is, in part, an attempt to overcome this limitation.

A second goal of Experiment 2 will be to evaluate another possible explanation for the large differences in the size of the uncertainty effect that appear to depend only on changes in the way that responses are made. It was only as we considered the results from Experiment 1 that we appreciated the possible importance of another difference between keypress and touching responses. For touching responses, the stimuli, the response targets, and visual feedback about the effector that is actually making the movement are in the same spatial frame of reference; we will call these direct responses. We consider keypress responses to be an example of displaced responses, since the stimuli are in one spatial reference, the actual movement targets are in a second frame and any visual feedback, used to guide the movement effector, is displaced from the response to the stimulus frame. Given this difference, it is possible that the uncertainty increase associated with b_{ES}^{Key}, a quantity that our model ascribes to effector selection, actually reflects the time required to map the intended response from one spatial frame of reference to another. Although it is not clear to us why the time required to do this mapping would increase with N_E, as would be necessary for this explanation to work, we also cannot rule out the possibility that it does. To explore this possibility, Experiment 2 will provide a well-planned comparison of direct and displaced movement conditions controlling both N_E and N_A.

Experiment 2

This experiment was designed to isolate effector selection and, by doing so, to provide further insights into the properties of this process. This was accomplished by using touching responses, with highly compatible S-R mappings, that, as shown by Experiment 1, minimize, if not eliminate, reaction time increases due to the S-R mapping process. Thus, all uncertainty effects should depend on N_E and, controlling for the N_E effects, there should be no effect of N_A. To provide a strong test of this prediction, N_A was varied from one to 18, a wider range than is typically studied.

As shown in Figure 7, the touching responses were made using three fingers on each hand. Thus, there could be from one to six effectors. Although it might have been nice to have taken N_E up to eight or ten, with the setup we used it was awkward to make touching movements with either the little finger or the thumb. One interesting aspect of this method of varying N_E is that the number of hands, one or two, could be crossed with the number of fingers per hand, one or three, to produce the four conditions studied. Thus, in principle, we should be able to determine whether the selection is made homogenously across the full set of effectors or, instead, whether there are separate, perhaps hierarchically organized selections made at the level of hands and fingers. For example, Rosenbaum and Kornblum (1982) have suggested that the process of response preparation and, by inference effector selection, are different for two fingers on the same hand versus two fingers on different hands.

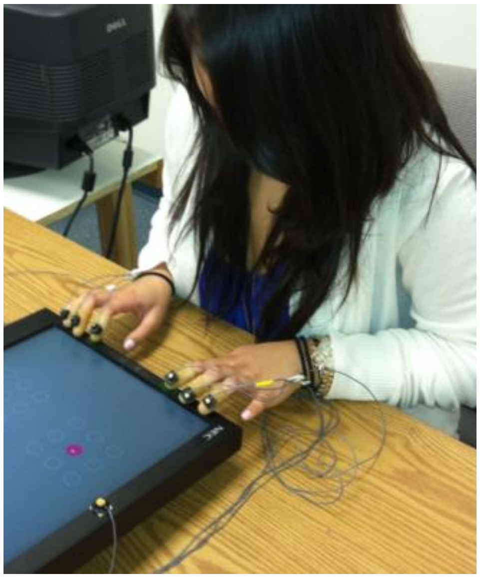

Figure 7: Setup for Experiment 2. Optotrak emitters on six of the P’s fingers and on the case of the flat-panel display allow tracking of the response movements to target locations on the display screen.

In addition to studying effector selection, this experiment also contrasted direct and displaced movement conditions. In the direct movement condition, as in the touching movements studied in Experiment 1, the P moved his/her finger directly to the target location on the screen. The displaced movement condition is somewhat analogous to moving a mouse, where physical movements in one frame of reference control cursor movements in a different frame of reference that contains the movement targets. To make the direct and displaced conditions in this experiment as comparable as possible, the movements required in the displaced condition were identical to those in the direct condition – i.e., the movements started from the same location in both conditions and, at the end of a correct movement, the finger would touch the display screen in the exact same place in both the direct and the displaced conditions. However, since, as shown in Figure 8, the movement targets were displaced away from the P on the display screen, instead of moving the finger to actually touch the target, the P was moving a displaced cursor, whose movements were yoked to the movements of a finger so that the cursor would be on the target disk when the finger touched the display screen.

Methods

Participants

There were 8 participants (6 male, 2 female). Each had 20/20 corrected vision, and all were right-handed. The UCI Institutional Review Board approved the experiment.

Apparatus and Stimuli

A PC running a custom application written in Matlab using PsychToolbox version 2.54 was used to present stimuli and record responses. An NEC Model L196H5 19”, flat-screen, LCD in “portrait” orientation was used to present stimuli and movement response targets. As shown in Figure 7, this panel display was affixed to a table top. An Optotrak Model 3020 recorded, with a 100 Hz sampling rate, the x, y, and z coordinates of infrared emitters. Three emitters mounted on the LCD’s case were used to create a frame of reference for coordinates relative to the LCD screen. Six additional emitters, attached to appropriately sized Swingline Rubber Finger Tips, were worn by the P on the index, middle, and ring fingers of his/her left and right hands. These emitters were used to track simultaneously the position of all six fingers throughout each trial.

As shown in Figure 8, stimuli and potential response targets were disks laid out in two 3 x 3 grids, one on either side of fixation. The disks, 17.5 mm in diameter (1.25° of visual angle at the nominal viewing distance to the fixation of 80 cm), were spaced 30 mm (2.15°) apart horizontally and 25 mm (1.79°) apart vertically. The rightmost location in the left grid and the leftmost location in the right grid were each 30 mm (2.15°) from fixation. The two panels of Figure 8 also show the layouts used for the direct movement and displaced movement conditions. In both conditions, a P’s fingers were placed on the display case, just below the visible display. In the direct condition, the bottom row of locations was 110 mm from the starting points of the fingers on the display case, and the top row of locations was 50 mm further away. The cursors were filled disks, 2 mm (.29°) in diameter.

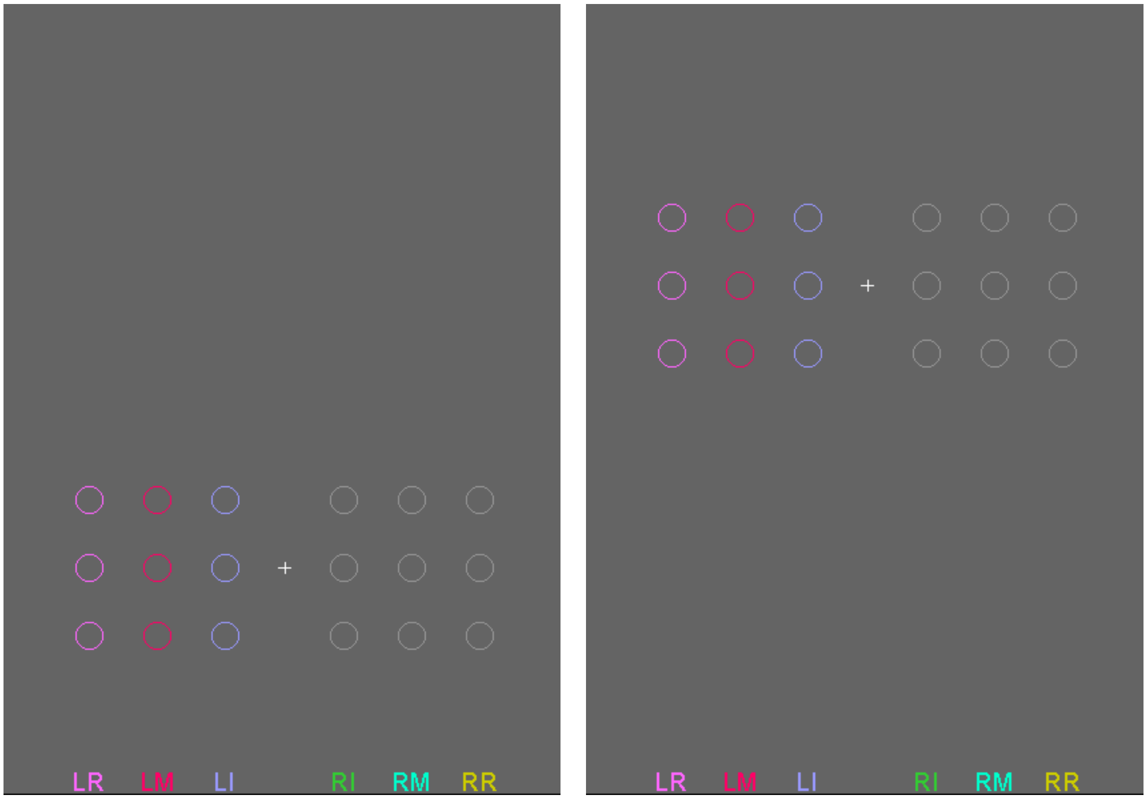

Figure 8: Sample initial display showing the layout of the stimulus and response locations. The panel on the left shows the layout for the direct movement condition; the panel on the right for the displaced movement condition. The two-letter codes at the bottom of each panel show the colors associated with each of the effectors. See text for more explanation.

Design

The primary factors in this experiment were N_A, the number of active S-R alternatives, and N_E, the number of effectors, which can be broken down by effector type: N_H, the number of hands, and $N_{F/H}$, the number of fingers used on each hand. The entries in Table 5 show the levels of these factors that were studied and how these and an additional factor were combined to determine the 16 conditions studied in this experiment. The third factor was whether the stimulus and response-target locations were all located on a single side of fixation or were symmetrically distributed on both sides of fixation.

The number before the × symbol in the Table 5 entries indicates the number of variants of a condition that were studied. For example, in the cell with $N_E = 1$ and $N_A = 1$ in Table 5, this number is 6 because six variations of this condition, one with each of the six fingers as the effector, were run separately in the experiment. In general, however, the analyses did not focus on these variations.

The number after the × symbol shows the total number of trials run for each variant of a condition. Each variation was run as a separate block of trials. Also, in order to give feedback at

Table 5: Conditions included in the 35 blocks of the design. The conditions are broken down according to the total number of effectors, N_E, the number of hands, N_H, the number of fingers used per hand, $N_{F/H}$, and whether the S-R pairs were located only on one side of fixation or on both sides of fixation. The number before the × symbol indicates the number of variants of a condition that were studied. Examples of variants are different target locations or different effectors. The number after the × symbol gives the total number of trials run in the condition. If this is followed by the string "/2", this means that the trials were divided into two blocks run separately.

				Stimulus and Response-Target Locations							
				One Side of Fixation					Both Sides of Fixation		
N_E	N_H	$N_{F/H}$	$N_A =$	1	2	3	6	9	2	6	18
1	1	1		6×5	2×8	2×12	2×18	2×18	2×8	2×18	2×36/2
2	2	1							1×8	1×18	1×36/2
3	1	3				2×12	2×18	2×18			
6	2	3								1×18	1×36/2

regular intervals, for the three conditions with $N_A = 18$, the total set of trials was divided into two blocks of 18 trials that were run separately. This is indicated by the "/2" marking in Table 5. Taking these split conditions into account, the full design required 35 blocks that were divided across two sessions of roughly an hour apiece. The order of conditions within and across sessions was randomized separately for each P. The two test sessions were preceded by a practice session that included only a selected, but representative, subset of the conditions and their variations so that this practice session could also be completed in an hour. In addition, the first trial in each test block was treated as a practice trial.

There are many ways that S-R combinations could have been chosen even within the constraints of Table 5. There were two principles guiding these choices. The first was that the S-R mapping had to be as straightforward as possible in order to minimize the S-R mapping effects. Second, the sets of locations were chosen to be symmetric around the center of the 3x3 grids and the fixation, although this symmetry was often only achieved across the variations of a condition. These two guiding principles led to the following six rules. (see Appendix in online supplemental materials for the actual S-R combinations used for each variant of the conditions.) (a) For conditions involving three fingers, each finger was mapped to the spatially compatible column of the 3x3grid. (b) If a condition involved one finger, it was always the index finger. (c) If there were two target locations, they were either the left and right locations of the middle row or the middle locations in the left and right 3x3 grids. The next three rules applied in conditions involving both one or three fingers. (d) If there were three locations, all three locations were on the middle row. (e) If there were six locations, either all the locations were on the top and bottom row on one side or they were on the middle row on both sides. (f) If there were 9 locations, all of the locations in a 3x3 grid were used.

The entire three-session design was completed twice by each P, once in the direct movement condition and once in the displaced movement condition. The order of these two conditions was counterbalanced across Ps.

Repetition was treated as an independent variable because studies have shown that subjects are generally faster to respond when targets repeat (Kornblum, 1969). This is particularly an issue when, as in this experiment, the size of the set of possible targets varies. To appreciate the importance of taking this variable into account, consider that when there were two possible targets, repetitions were three times more likely to occur than they were when there were six possible targets.

To discourage Ps from anticipating the indicator stimulus and to keep their attention on the fixation even when the stimuli were all on one side, from 10%-20% additional catch trials were added, depending on the number of trials in a block. On these trials, instead of the indicator stimulus, one of 10 low-contrast, noise-obscured letters was presented at fixation to be identified. Prior pilot testing was used to ensure that these letters could be identified with greater than 90% accuracy when viewed at fixation but with less than 30% accuracy when viewed 68.75 mm (4.92°) in the periphery – the distance of the center location in the 3x3 grids to fixation. Ps were given 5 minutes of practice identifying these letters at fixation before the start of the first session. They also received feedback on their catch trial performance at the end of each block.

Procedures

Each session began with a calibration process in which the P touched each finger to a set of locations that spanned the movement target area of the display. From these data and data from three emitters permanently placed on the case of the display, a linear transformation was estimated that mapped the screen and finger coordinates into the three-dimensional coordinate system of the OptoTrak. At the start of every block, Ps were led through a quick version of the calibration procedure to check that the registration remained accurate. If this revealed issues, the full calibration was repeated.

At the start of each trial, a display was presented showing the S-R mappings for that trial. The Panels of Figure 8 show an example of such a display for a condition in which the three fingers on the left hand will be used to touch one of nine possible targets. The nine gray circles to the right of fixation indicate locations that are not involved in the movements in this block. The nine colored circles to the left of fixation are the potential movement targets. The color of each circle indicates the effector to be used for movements when that location is the target. The code for these colors is shown in Figure 8, by the two letter codes at the bottom of the screen. As described below, however, Ps did not see these codes but rather colored disks above each starting finger location.

In addition to indicating the possible stimuli/targets and the stimulus-to-effector mapping, the initial display also contained the message “Move hands to their home positions.” In response, the P was to position the index, middle, and ring fingers of both hands on predetermined locations on the display case. At the bottom of the display, in roughly the locations of the six two-letter codes that refer to each of the 6 effectors in Figure 8, was an outline circle, displayed using the same color as the two letter codes in the figure. As each finger was moved into place, these became filled circles. If a finger subsequently moved too far away, the outline circle was redisplayed. Once all six fingers had remained within 8 mm of the starting position for 0.5 s, the main part of the trial began. From this point, the position of all six effectors was recorded until

0.5 s after the response movement was deemed to have ended or some other event terminated the trial.

Both to help maintain attention at fixation and to minimize uncertainty about when the indicator stimulus would appear, the fixation mark was flashed off and then on twice with each interval lasting 0.4s. During this interval, the rest of the stimulus display remained unchanged. At the point when the flashing fixation would have reappeared for the second time, either a catch-trial letter was displayed at fixation or the indicator stimulus appeared. The indicator stimulus consisted of the gray interior of the circle at one of the possible target locations being redrawn with the effector color associated with that target. The appearance of the indicator stimulus began the reaction time period. If a response was not initiated within 1.5 s, an error message was displayed, a new trial was begun, and this particular trial was rerun later in the block.

The OptoTrak position recording system requires a clear line-of-sight path between an emitter and the three-camera array used to sense emitter positions. If the signal from any of the six effectors was lost or any of them moved more than 5 mm from its starting location before the indicator stimulus was displayed, the trial was restarted with an error message. The reaction time period was determined to have ended when any finger on the hand with the effector expected to complete the movement moved more than 5 mm from its resting position. The trial was immediately terminated if any finger on the other hand moved more than 10 mm and an error message was displayed. Any movement of more than 5 mm on a catch trial was also classified as an error.

Once the movement was initiated a dot that tracked the movement of the target effector was displayed. Although visible on direct movement trials, this cursor provided feedback to the P that was critical only on displaced movement trials.

The method used to determine that a movement had ended, depended on whether or not the trial was a catch trial. Catch trials were successfully ended when there had been no movement on either hand for 1.5 s. Figure 9 contains a sample trajectory that illustrates how the movement endpoint was determined for non-catch trials. The computer tracked the trajectory of the three effectors on the target hand (the hand with the effector expected to make the movements) in real time with an effective delay of between 20 ms and 30 ms. We noted that

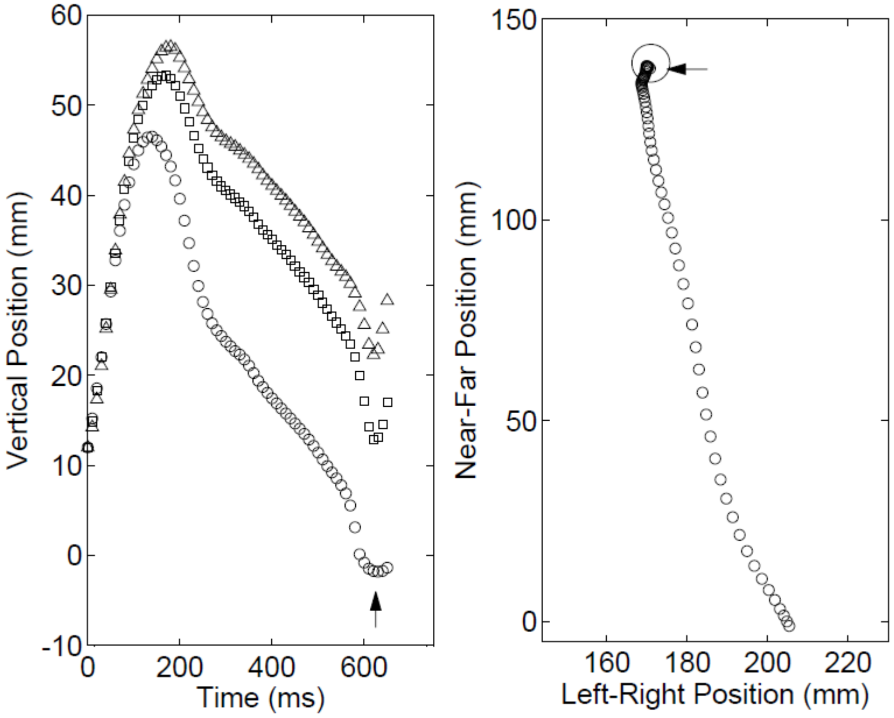

Figure 9: Sample movement trajectory illustrating the determination of the movement endpoint. The panel on the left shows the height of the three fingers on the target hand as a function of the time from the movement initiation. The circles are the index finger, which is, for this trial, the effector doing the touch, the squares and the triangles are the middle and index fingers respectively. The data points are spaced apart by 10 ms. The panel on the right shows the trajectory for just the index finger across the plane of the display. The movement begins at the bottom. The larger circle is the target disk. In both panels, the arrow points to the sample marked as the endpoint.

when the fingertip touched the display screen, the compression of the finger pad and its rubber tip produced OptoTrak samples that appeared to descend below the plane of the screen before rising back out again. We used this effect to mark the end of a movement. Specifically, a movement was considered to end when any effector that broke the plane of the screen reached its maximum depth of penetration.

If the end of the movement was not registered in 3.0 s, the trial was stopped, a message was displayed, and the trial was later rerun. Typically, this happened because of a failure of the heuristic designed to detect the end of a movement. A similar action was taken if, during the course of the movement, the OptoTrak could not record the position of the emitter tracking the target finger. This same criterion was not applied to the other fingers on the target hand to avoid the inconvenience of having to rerun trials for this reason. The instructions, like those of a discrete Fitts task, emphasized minimizing the total time to complete the movement and treated all movements ending within the target circle as correct and all movements ending outside the target circle as errors (Fitts, 1954). When a catch trial was over, a message was displayed asking the P to report the letter that had been displayed. The experimenter typed this verbal response into the computer. A second message was then displayed indicating whether or not the response was correct.

For non-catch trials, the stimulus array was redisplayed with the cursor indicating the location of the movement's endpoint. If the movement ended up outside of the target, went to the wrong target, or if the wrong effector completed the movement, an error message was displayed. Trials with errors were rerun later in the block. If there was no error, a message giving the total movement time was displayed.

Block Feedback and Bonuses

After the last trial in each block, the display was cleared and a message was presented summarizing for the P his/her performance and providing a score for the block. In addition to the score, this summary included the average total movement time, in hundredths of a second, the number of catch-trial errors, and the count of other subject errors: i.e., trials on which the movement missed the target, used the wrong effector, etc., but not trials on which an effector was lost. The score was calculated as the sum of the average total movement time (in hundredths of a second; typically, about 95 in the direct movement condition and 110 in the displaced movement condition), three points for each missed target and five points for each catch-trial error. The P received a bonus of $.05 for each block for which the score was less than or equal to a target score for that block. The bonuses were designed to reward good performance. Twelve separate target scores were maintained for each P, for each level of N_A in the direct- and displaced-movement conditions. At the end of each block, the appropriate one of these scores was adjusted based on the average score for that block. Let T_i be the target score for block i and S_i the average score for that block. T_1 was set to 100 for target scores associated with the direct-movement conditions and 120 for target scores associated with the displaced-movement conditions. Subsequent target scores were computed according to a recursive formula.

$$T_{i+1} = \begin{cases} T_i - 0.67\,(T_i - S) & \text{if } T_i \geq S_i \\ T_i - 0.25\,(T_i - S) & \text{if } T_i < S_i \end{cases}$$

Results

Errors

Table 6 summarizes the occurrence of errors of various types in this experiment. All of the errors listed in the top section of the table were detected as they occurred, so that it was possible to rerun the exact combination of target and effector for that trial within the same block, and so maintain the balance of those conditions. This was not possible for trials with long reaction

Table 6: Summary of Errors in Experiment 2

	Movement Condition	
	Direct	Displaced
Missed target	2.7%	2.5%
Wrong effector completed movement and hit target	2.6%	2.1%
Wrong effector completed movement and missed target	0.08%	0.03%
Non-target hand moved during target-hand movement	0.03%	0.24%
Non-target hand moved initially	0.26%	0.34%
Movement before stimulus	0.24%	0.18%
Movement took too long to begin	0.05%	0.03%
Movement took too long to finish	0.40%	0.42%
Lost emitter before movement	0.24%	0.34%
Lost sight of target effector marker	0.40%	0.03%
Long reaction time	0.40%	0.69%
Long duration	1.5%	0.85%

times or durations, since these were determined relative to the distributions in each condition. A reaction time was deemed long if it was more than three times the inter-quartile range away from the median of the distribution for that P in that condition after a log transformation. The same criterion, without the log transformation, was used to identify long durations. An examination of the trajectories of trials with long durations revealed that all but three of these were otherwise normal movements for which the criterion to identify the end of a movement failed.

There were no errors in which it appeared that the movement was directed at the wrong target, and only 2.6% of the movements ended outside of the intended target. As might be expected, there were slightly more of these missed targets errors for movements made with the (non-dominant) left hand and for movements made with the ring fingers than for those made with the index or middle fingers.

Interestingly, there were almost as many errors in which the wrong effector correctly completed the movement to the intended target. Four out of the eight Ps were responsible for over 96% of these errors, with 44% of these errors having been produced by a single P. Although there were only 182 of these errors, there were some strong, and possibly suggestive, patterns in them. First, the incorrect effector never involved the wrong hand. There was, however, a strong tendency for movements that were to have been made by the middle finger to be completed by the ring finger; this pattern accounted for two-thirds of these errors, and 70% of these involved the right (dominant) hand. Although it seemed plausible, there was no evidence that these finger-substitution errors reflected a tendency to use the finger naturally associated with a target location instead of the intended effector. [iii]

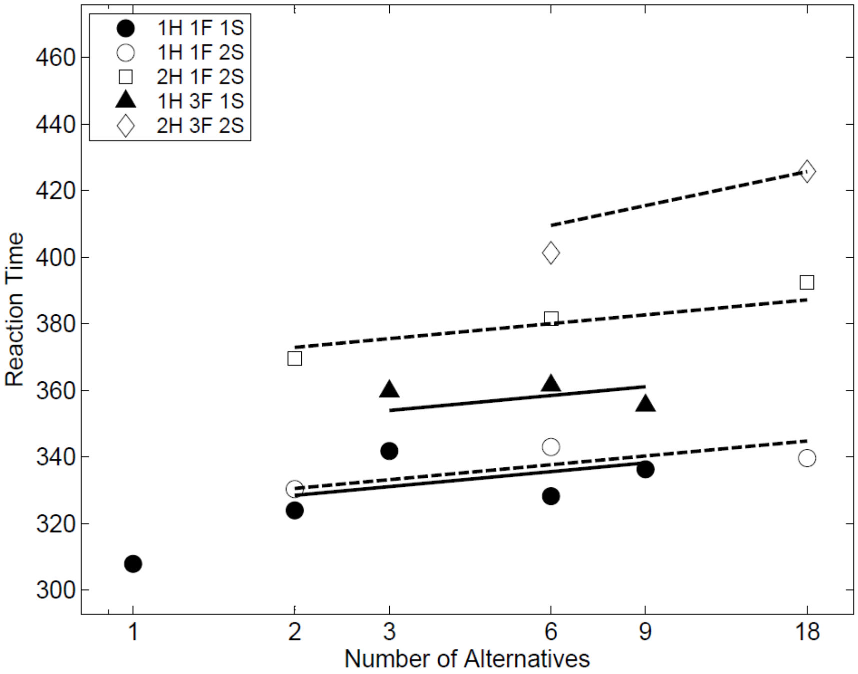

Figure 10: Reaction time data from the switch trials in Experiment2 averaged over Ps and the direct and displaced movement conditions.
The reaction times in each of the 16 conditions are plotted against $\boldsymbol{N_A}$, the number of S-R alternatives. The legend identifies conditions represented by the five different plotting symbols in terms of the number of effectors, broken down by the number of hands (H) and number of fingers (F), whether the stimuli were on only one (filled symbols) or both (open symbols) sides of fixation (S). So, for example, the open squares are used to mark the three data points, with N_A values of 2, 6, and 18, for touching movements that could be made with either hand, but that were always made with the middle finger, to locations on both sides of fixation. The lines show the predictions of a descriptive model, fit to all the data, which will be described later. Solid lines are the predictions for conditions with stimuli on only one side of the fixation; dashed lines for conditions with stimuli on both sides.

Reaction Times

Figure 10 summarizes the reaction times on the switch trials averaged across the direct and displaced movement conditions. Only data from switch trials are included in this summary for two reasons. First, as discussed for Experiment 1, simply averaging switch and repetition trials can create the appearance of uncertainty effects even if none are present. In addition, however, with larger values of N_A, a given P might have few, or in some cases, no repetition trials in some conditions. The data in this figure were averaged across the direct and displaced movement conditions because, as will be documented below, this factor was found to be associated only with effects that were additive with the other factors of interest. The data in this figure excludes all of the trials listed as errors in Table 6.

Simply looking at Figure 10, it is clear from the nearly horizontal fitted functions that the effect solely attributable to N_A, the number of S-R alternatives, is small at best. There are, however,

Table 7: Parameters included in the descriptive model used for Experiment 2.

Symbol	Description
t_{Add}	Reaction time for the direct-movement condition with stimuli on only 1 side and $N_A = 2$ & $N_E = 1$
t_{Task}	Reaction time increment associated with the displaced-movement condition
$t_{2\mathrm{Side}}$	Reaction time increment associated with stimuli on both sides of fixation
$b_{SR}^{N_E \leq 3}$	Uncertainty slope due to a doubling in N_A for conditions with $N_E \leq 3$
$b_{SR}^{N_E = 6}$	Uncertainty slope due to a doubling in N_A for conditions with $N_E = 6$
$b_{ES}^{N_{Hands}}$	Uncertainty slope due to a doubling in the number of hands as possible effectors
$b_{ES}^{N_{Fings}}$	Uncertainty slope due to a doubling in the number of fingers as possible effectors
p_{check}	Probability of checking for an S-R repetition
t_{check}	Time increment required when checking for an S-R repetition

larger differences associated with the number and type of effectors. One surprising aspect of these effector differences is that the reaction time for movements made selecting among three effectors (one of three fingers on one hand; the data marked with filled triangles; the solid line shows the predictions for these data from the fit of the model to be described) is less than that for movements made selecting among two effectors (the middle finger on either the right or the left hand; the data marked with open squares; the dashed line is from the fit of the model). In addition, there is, at most, a small increase in reaction time when the stimuli are on both sides of the fixation rather than all being on one side. This can be seen most easily by looking at the data for $N_E = 1$ in Figure 10. The filled circles mark the data from conditions with all stimuli/targets on one side of fixation. The open circles mark the data from conditions with equal numbers of the stimuli/targets on both sides of fixation. The solid line is the model fit for the data marked by filled circles, and the dashed line, which is only slightly above the solid line, is the fit for the open circles.

As in Experiment 1, a descriptive model based on Equations 3 and 4 was fit to these data. Table 7 identifies the 9 parameters of the resulting model, and Table 8 summarizes their estimates. Understanding the results of this experiment through the fit of this model has two advantages. It provides a systematic way to incorporate the data from both the switch and the repeat trials. The estimates of the model's parameters also provide direct quantitative assessments that can be related to specific questions of interest in these data. Because the occurrence of the effectors and stimulus/target locations was not perfectly balanced across the 16 conditions, we explored variations of this model that included additional terms to account for effects due to the effector used or the location of the stimulus/target. However, since including these terms resulted in only small changes in the parameter estimates (typically less than 1%) and had no effect on the overall pattern of results, what we report here is based on a model that did not include those terms.

Before turning to the central question, it will simplify the data presentation to examine the effect of task – i.e., direct versus displaced movements – on reaction time. The parameter estimates for t_{Task} provide strong evidence that movements in the displaced movement condition took longer to initiate. However, we found no evidence for any other effects associated with task. Initially, the model outlined in Table 7 (but without the task parameter) was fit separately to the data from the direct and displaced movement conditions. Paired t-tests comparing the resulting parameter estimates across task found evidence for a difference only for t_{Add} (this comparison is the same as that for t_{Task} in Table 8); for the other seven comparisons, *t*(7) ranged from a high of 1.30 down to 0.45 (the Bayes factors for a difference associated with these t-values range from 0.50 to 0.34). Based on these preliminary results, the parameter estimates in Table 8 are based on data averaged across both two conditions.

As noted above, there is little evidence that reaction times were slower in the condition with stimuli on both sides of fixation. This result presumably reflects the use of catch trials to encourage Ps to keep their eyes focused on the fixation until the stimulus appeared, even when all of the stimulus/response combinations were all on one side of fixation. The remaining results are consistent with the predictions based on Experiment 1. As hypothesized, the use of a highly-compatible, spatial indicator stimulus led to uncertainty effects due to S-R mapping that were, at most, quite small. The almost horizontal lines in Figure 10, reflect this outcome. An initial version of this model included separate slope estimates for each level of N_E. Because these estimates were close to zero for all but the $N_E = 6$, in this model the other estimates were combined. This combined estimate of $b_{SR}^{N_E \leq 3}$confirms that there was little or no evidence supporting the existence of an uncertainty effect associated with N_A when the task involved either just a single, known effector, the selection of the appropriate effector among two effectors (the middle finger on either hand), or the selection of the appropriate effector among three effectors (the three fingers on one hand). By contrast, the estimate of $b_{SR}^{N_E=6}$ provides strong evidence for an uncertainty effect associated with N_A for movements in which the P had to select the appropriate effector from among six effectors (the three fingers on both hands). Although the evidence for this effect was strong, its size compared with the size of uncertainty effects typically observed in choice reaction time tasks, was quite small: 5.5 ms per doubling of N_A, which is less than 5% of the uncertainty effects typically observed.

Table 8: Parameter estimates for the descriptive model used to summarize reaction times in Experiment 2.

		t_{Add}	t_{Task}	$t_{2\text{Side}}$	$b_{SR}^{N_E\leq3}$	$b_{SR}^{N_E=6}$	b_{ES}^{Hands}	b_{ES}^{Fings}	p_{check}	t_{check}
Participant	1	300	45.1	-10.2	8.1	10.6	55.2	12.2	0.378	38.8
	2	282	16.4	17.3	1.5	5.9	11.7	12.0	0.849	33.1
	3	263	11.8	6.9	-1.1	4.3	22.7	17.4	0.337	33.7
	4	276	24.0	-1.7	4.5	5.6	32.8	7.6	0.493	30.3
	5	309	3.9	8.7	-0.6	10.1	43.7	22.7	0.356	35.5
	6	256	35.9	-3.9	4.6	4.9	40.3	20.1	0.294	30.5
	7	373	21.3	3.7	4.8	1.7	76.3	17.7	0.000	19.0
	8	364	21.5	13.3	-2.5	0.5	54.9	12.0	0.155	37.3
	Mean	303	22.5	4.2	2.4	5.5	42.2	15.2	0.358	32.3
	SD	44	13.0	9.2	3.6	3.6	20.3	5.1	0.249	6.1
95% Interval	Upper	340	33.4	11.9	5.5	8.4	59.2	19.4	0.566	37.4
	Lower	266	11.6	-3.4	-0.6	2.5	25.2	11.0	0.150	27.1
	t(7)	19.436	4.881	1.308	1.883	4.325	5.864	8.507	4.067	14.848
	p	0.000	0.002	0.232	0.102	0.003	0.001	0.000	0.005	0.000
	Bayes Factor	>1000	25.7	1.55	1.13	15.1	60.7	410	11.7	>1000

The uncertainty effects associated with effector selection are reflected in the estimates of $b_{ES}^{Hands}$and b_{ES}^{Fings}. Both of these slope estimates are substantially larger than that due to S-R mapping in this experiment. Interestingly, the estimate of the slope for the effect due to selecting between hands, 42.2 ms per doubling is almost three times that of the slope due to fingers, 15.2 ms per doubling.

Movement Durations

A 9-parameter linear model was used to summarize the movement durations. Most of the parameters of this model are analogous to those described in Table 7 for the latencies. The duration model is simpler than that for latencies in part because the p_{check} and t_{check} parameters were replaced by a single, additive parameter for the increment to movement duration on repetition trials, t_{Rep}. It was also only necessary to include a single term to summarize effects due to the number of S-R alternatives. Because, such an effect, if it is present, is unlikely to be due to stimulus-response mapping, rather than b_{SR}, this parameter is labelled, b_{NA} with the subscript *NA* alluding to the number of alternatives. For similar reasons, the terms b_{ES}^{Hands} and b_{ES}^{Fings} in the latency model appear as b_{Hands} and $b_{Fingers}$ in the duration model since any increases in durations due to the number of hands or fingers involved are, presumably, not due to effector selection (but more on this later). A more substantive change reflected the general tendency for movement durations to be strongly influenced by movement distance. Depending on the effector used and the target location, straight-line movement distances ranged from 96 mm to 246 mm with a mean of 160 mm. Because the frequency of occurrence of the effectors and stimulus/target locations was not perfectly balanced across the 16 conditions (Appendix in online supplemental materials) the average movement distance varied across conditions. To keep these differences from altering other parameter estimates, the model included a slope term, b_{Dist} describing the linear increase of movement duration (in ms) associated with each mm increase in movement distance. A second parameter, b_{Dist}^{Disp}, was included to capture any increment in this slope in the displaced-movement condition compared with the direct-movement condition.

Table 9 presents summaries of the nine parameters based on the fit of this model. The additive term, t_{Add}, estimates the movement duration for the “reference” movement. Given the way the design matrix for this model was coded, the reference movement is a 160 mm movement made on a switch trial in the direct-movement condition with a known hand and finger and $N_A = 1$. The parameter t_{Task} is an estimate of the substantial increase in duration for the displaced-movement condition – i.e., a condition in which the movement feedback consists of a cursor, controlled by the finger movement, moving to a target location displaced from endpoint of the finger movement itself. The next two parameters, $t_{2\text{Side}}$ and t_{Rep}, document the lack of evidence for additive increments in movement duration either when the stimuli/targets were on both sides of fixation or when the stimulus/response repeated that of the previous trial, respectively.

The parameter b_{Dist} reflects a strong, linear relation between movement duration and distance: on average, for each mm that a movement was longer (shorter) than the 160 mm average, the movement duration increased (decreased) by 10 ms. There is moderate evidence that this slope is more than 70% larger in the displaced-movement condition. These were the only two ways

Table 9: Parameter estimates for the descriptive model used to summarize durations in Experiment 2.

		t_{Add}	t_{Task}	$t_{2\text{Side}}$	t_{Rep}	b_{Dist}	b_{Dist}^{Disp}	b_{NA}	b_{Hands}	$b_{Fingers}$
Participant	1	343	278	-18.2	6.1	10.85	7.12	11.1	24.6	8.2
	2	540	273	-13.1	-14.4	13.71	8.85	-2.1	13.2	21.0
	3	493	46	86.6	35.5	7.11	3.09	16.3	-54.0	20.7
	4	466	219	0.2	-17.9	8.68	9.71	-0.5	-30.5	23.7
	5	497	245	-16.5	-13.4	10.27	4.85	-2.4	27.8	27.9
	6	315	269	-15.5	14.8	6.97	6.35	12.2	8.8	11.3
	7	807	270	-14.4	-6.3	14.64	21.01	22.6	9.3	0.9
	8	896	98	36.6	68.2	8.40	-3.11	-4.6	-85.8	50.1
	Mean	545	212	5.7	9.1	10.08	7.23	6.5	-10.8	20.5
	SD	206	90	37.4	29.9	2.87	6.86	10.2	41.4	14.9
95%	Upper	717	287	37.0	34.0	12.48	12.97	15.1	23.8	33.0
Interval	Lower	372	137	-25.6	-15.9	7.68	1.50	-2.0	-45.4	8.0
	t(7)	7.478	6.701	0.432	0.857	9.916	2.983	1.807	-0.739	3.875
	p	0.000	0.000	0.679	0.420	0.000	0.020	0.114	0.484	0.006
	Bayes Factor	207	117	0.364	0.452	948	3.75	1.04	0.420	9.65

that displaced movements were found to differ from direct movements. (The largest of the $t(7)$ values for the other comparisons between the direct- and displaced-movement conditions was 0.971, with an associated Bayes factor of 0.490.)

The parameter B_{NA} reflects the lack of an effect of the number of S-R alternatives on movement duration. Similarly, the b_{Hands} parameter suggests little evidence for a difference in duration for conditions in which the movement might be either of the two hands versus one hand. By contrast, there was moderate evidence for an increase in movement duration for conditions in which the movement might be completed by any of three fingers versus a single, known finger.

Discussion

This experiment succeeded in its three primary goals. The first was to provide a more stringent test of the hypothesis that S-R mapping contributes little to uncertainty effects for touching movements when the indicator stimulus is spatial and the mappings are compatible. All of the S-R mappings used in this study were highly compatible, and consequently (as hypothesized) variations in the number of S-R alternatives had little influence on performance. Even with conditions that included as many as 16 S-R alternatives, when the effector selection involved three or fewer effectors, the slope describing the increase in reaction time associated with N_A was small, if not effectively zero. If the effector had to be selected from among six fingers, there was moderate evidence that the slope associated with N_A was greater than zero; however, this slope is small: on the order of 5% of that typically reported for uncertainty effects.

By minimizing uncertainty effects due to the S-R mapping, we were able to focus more clearly on the second goal, to explore the properties of the effector-selection process using more than two effectors and using effectors of different types: hands versus fingers. Consistent with the results of Experiment 1, there was a sizeable increase in reaction time that depended on the number of effectors from which the movement effector had to be selected. Unexpectedly, the effector-selection slope estimate was much larger when the selection was between hands (42 ms per doubling in the number of effectors) than between the fingers on a hand (15 ms per doubling). In line with proposals of Rosenbaum and Kornblum (1982), this difference may signal either that effector selection subsumes multiple processes, or else that it treats hands and fingers differently. In this connection, it is reasonable to ask whether there is an interaction between having to choose between hands and having to choose between fingers. The data for the conditions with $N_A = 6$ enable us to address this question directly. The reaction time increase across conditions requiring the P to select a single finger from one vs. two hands was 45.8 ms. The analogous increase across conditions requiring the P to select one of three fingers from one vs. two hands was 39.8 ms. The difference between these two increases, 6.0 ms [sd = 42.2, 95% confidence interval -29↔41, t(7) = 0.403, Bayes Factor = 0.36], is a measure of this interaction. If the specification of hand and finger is done hierarchically in a proximal to distal manner as suggested by Rosenbaum and Kornblum, we would have expected this interaction to be large, since prior information about the finger to be used should only be useful if the hand were also known in advance. However, although the magnitude of this interaction is small, it does not provide strong evidence against this prediction because the large uncertainty of this estimate means that the support for additivity is also weak.

The third goal of this experiment was to explore how the difference between direct versus displaced movements affected choice reaction time. In the direct condition, the stimulus, the location of the movement target, and any visual feedback about the location of the actual effector are all available in a common spatial frame of reference; by contrast, in the displaced condition, the frame of reference for the response information is different than that of the stimulus. Although there was strong evidence for a direct/displaced task difference on reaction time (t_{Task} in Table 8), this effect was small, 22.5 ms and did not vary with N_A or N_E. This finding argues strongly against the difference between direct and displaced movements as the explanation for the large differences in the size of the uncertainty effect that appears to depend only on changes in the way that responses are made.

Although the effects of the direct/displaced task difference on reaction time were small, there were quite large effects of this manipulation on movement durations (see the parameters t_{Task} and b_{Dist}^{Disp} in Table 9). Displacing the movement feedback increased the duration in the reference condition by almost 40%; it also increased the influence of movement distance on duration by over 70%. We are not the first to have found that, for certain types of manual interaction, the duration cost of displaced feedback can make direct touches, as on a touchscreen, preferable to displaced movements, as with a mouse (Forlines, Wigdor, Shen, & Balakrishnan, 2007).

Considering the reaction data together with the movement duration data suggests a possible explanation for the large difference between the b_{ES}^{Hands} estimate and the b_{ES}^{Fings}estimate (Table 8). The experimental procedures required Ps to commit to a particular hand before initiating a movement becuase a noticeable movement by the incorrect hand was flagged as an error and the trial was rerun. There was, necessarily, not a similar emphasis to enforce selection of the to-be-used finger before any movement was initiated. If, in the conditions that involved selection among three possible fingers, some of the time required to complete this selection occurred after movement initiation, we might expect to see an associated increase in the movement durations. Consistent with this expectation, there was moderately strong evidence for an increase in duration due to finger selection. The estimate of the $b_{Fingers}$ slope parameter (Table 9) was 20.5 ms per doubling. A possible interpretation is that finger selection continued after movement initiation; this interpretation is bolstered by the lack of a similar duration effect associated with the hands. Suggestively, the sum of the reaction time and duration slope terms associated with finger selection, 35.7 ms per doubling, is certainly within measurement error of the reaction time slope estimate for hand selection, 42 ms per doubling. The similarity of these two values might be seen as at least weak support for the hypothesis that effector selection is a single process that treats hands and fingers equivalently: i.e., simply as effectors. If this theory is true, then effector selection must continue after response initiation.

We have been unable to find any clear evidence that finger selection continues after movement onset. Consider a specific example of the type of evidence we have searched for, but could not find, to support the suggestion that finger selection may not be completed by the time a movement has been initiated. If Ps initiated movements before the finger was selected, overlapping the determination of the finger with the initial portion of the movement, then we might expect to see some difference when comparing movement trajectories from conditions where the finger was known in advance with conditions that required selection of one from the three fingers. With the finger known in advance, that specification could be reflected in the relative paths of the movement trajectories for the three fingers from the start of the movement. With the finger still to be specified when the movement began, either the paths of the three fingers would be initially undifferentiated or there would be a one in three chance that the wrong finger would appear, initially, to be following the characteristic trajectory of the finger that would ultimately compete the response. However, several analyses comparing the movement trajectories from one- versus three-finger conditions failed to reveal any clear differences. The left panel of Fig. 9 illustrates the sort of difference we looked for. It shows that the effector that will complete the movement is held lower, closer to the surface of the display, than both of the other fingers and that this height difference emerges early in a movement. Thus, the current results cannot resolve definitively either of our two outstanding questions about effector selection: (a) why the effector selection cost for hands is almost three times larger than that for fingers in the reaction time data, and (b) whether effector selection is a single process, applying uniformly to hands and fingers, or something more complicated.

General Discussion

The Importance of Effector Selection

In a standard variation of the choice reaction time task, the P has to press an unknown one of N_A buttons as quickly as possible in response to a light that flashes on directly above it. Hick's Law states that response time in such tasks increases linearly with each doubling of N_A. For over half a century, such uncertainty effects have been ascribed primarily to the time taken to map that stimulus to the associated response. The central message of this paper is that little if any of the uncertainty effect in this particular, but standard, variant of the choice reaction time task is due to S-R mapping. Like many choice reaction time tasks, this standard variant confounds the number of potential response effectors (N_E) with the number of alternative targets (N_A). The current study decouples these two factors and demonstrates conclusively that the slowing that has been attributed to N_A in this task variant is actually due to the process of selecting the appropriate effector and thus related to N_E.

Our demonstration that S-R mapping is not important in the light-button task, should not be seen as a claim that S-R mapping cannot be an important contributor to uncertainty effects in choice reaction time tasks. We and others see large contributions of S-R mapping to uncertainty effects with symbolic indicator stimuli, and others have reported substantial effects for spatial indicator stimuli when the rule relating the position of the stimulus and that of the movement target is less straightforward; Dassonville, Lewis, Foster, and Ashe (1999) report an experiment that nicely illustrates both of these effects. However, in both of the experiments reported here as well as in our previous work, we see that, when stimuli are spatially linked to the responses in an intuitively simple layout, the time required for S-R mapping is sufficiently small that it often does not differ reliably from zero. What the current experiments add is a clear demonstration that, in tasks involving multiple effectors, selection among the effectors is a separate process that takes time; moreover, when the stimuli are spatially linked to the responses in an intuitively simple layout, effector selection is the predominant source of the observed uncertainty effect.

In addition to emphasizing the importance of effector selection, we believe that a second, important contribution of this research will be to clarify the phenomena that theories of S-R mapping must explain. Paul Fitts used the concept of S-R compatibility to refer to the fact that some tasks are easier or more difficult than others, not only because of the particular sets of stimuli and responses that are used, but because of the way in which individual stimuli and responses are paired with each other. Importantly, his two classic articles exploring this concept (Fitts & Seeger, 1953; Fitts & Deininger, 1954) were based on tasks involving a single, known effector. Whether this simply reflected a happy procedural choice – responses were made using a joystick in both of these papers – or a principled insight by Fitts is unclear. However, by the time of the influential review of Teichner and Krebs (1974), there seems to have been little concern about differentiating effects due to N_A from those due to N_E. This has substantially slowed progress toward a full understanding of the S-R mapping process and S-R compatibility effects. It seems likely that a re-examination of the literature on uncertainty effects that takes this concern into account will produce a clearer, and possibly simpler, understanding of S-R compatibility.

Are Hands and Fingers Both “Just” Effectors

Experiment 1 demonstrated how a model that includes effector selection, along with S-R mapping and the proper treatment of S-R repetitions, can explain the complex patterns of uncertainty effects observed in an experiment that includes manipulations of the indicator stimulus, response mode, and participant population chosen to maximize the variation in uncertainty effects. Experiment 2, by contrast, was designed to minimize uncertainty effects attributable to S-R mapping and thus focus on effector selection. The results of Experiment 2 suggest that selection among either hands or fingers contributes to the uncertainty effect. Looking just at the reaction time data suggests the contribution to uncertainty is larger for hand selection than for finger selection. However, this difference may be misleading. What if the selection process for fingers continued after the initiation of movement by the proper hand? We are led to consider this possibility because the experimental procedures penalized Ps for moving the wrong hand; however, there was no equivalent way to detect and thus penalize Ps for movements initiated before the proper finger had been selected. The combination of this procedural difference with three other observations suggests that what matters is the total number of effectors, not whether those effectors, the fingers, are on one hand or two. The three observations are that (a) there is evidence for an increase in movement durations associated with finger selection, but (b) no evidence for a movement duration increase associated with hand selection, and (c) that the increase in movement durations associated with finger selection was about the same size as the difference between the increase in latency associated with hands versus fingers. Although we like this neat picture, in which effectors are all treated equivalently and their layout does not matter, we are concerned that we were unable to find evidence to support this interpretation in movement trajectory differences that are consistent with selection of the target finger occurring during the movement. Thus, based on the data adduced here, we feel that this should remain an open issue.

Although the data reported here cannot resolve how hands and fingers fit together as effectors, they do provide some evidence against two specific ways that the separate selection of hands and fingers might interact. One possibility is that effector selection is hierarchical moving from proximal to distal, hands to fingers. Under this hypothesis, it might not help to know that only a particular finger could be the effector (for example, as in Experiment 2, the middle finger), if the hand is unknown. A second possibility is that selection of the hand and selection of the finger can be accomplished in parallel, or at least with a partial overlap. Since hand and finger selection were manipulated in a 2x2 factorial design in Experiment 2, we can ask if there was an interaction of their effects. If hand and finger selection were accomplished by separate mechanisms that are either hierarchically organized or that can be overlapped, we would expect to have seen an interaction, although in opposite directions for these two alternative organizations. However, there was no evidence for an interaction in either direction in Experiment 2. Unfortunately, although close to zero, the estimate of the interaction size is not well constrained by the data, so the claim for additivity is also weak at best.

Effector-Independence of Response Representations

The claim that effector selection is separate from S-R mapping suggests that the brain plans and initiates simple actions, such as those used as responses in choice reaction time tasks, using a response representation that is effector-independent. The idea that the plans for complex movement skills such as handwriting are effector-independent is an old one (e.g., Schmidt, 1975, 1988; Raibert, 1977; Stelmach, Mullins, & Teulings, 1984; Wright, 1990; Lindemann and Wright, 1998), so it seems natural to expect that this property would also apply to the simpler, discrete actions typically studied in these experiments. Recently, studies using multivoxel analysis of fMRI data have provided information about the brain networks that underlie effector-independent representations for simple actions and movement sequences (e.g., Gallivan, McLean, Smith, & Culham, 2011; Wiestler, Waters-Metenier, & Diedrichsen, 2014). Given this history of theorizing about effector-independence, it is surprising that it has taken so long for the implications of this concept to be developed within the choice reaction time literature.

Is S-R Mapping Bypassed for Straightforward Spatial Mappings?

Both of the experiments reported here make important use of data from conditions in which the indicator stimulus is spatial and the mapping to the response is straightforward. When this indicator stimulus is paired with a single, known effector, uncertainty effects have a slope at or close to zero. More generally, as Experiment 1 demonstrates, the contribution of S-R mapping to the uncertainty-effect slope remains small even when this indicator stimulus is paired with responses that involve multiple effectors, a situation in which the overall uncertainty effects are robust. This pattern of results raises the following question: Is the S-R mapping process involved at all in tasks with a spatial indicator stimulus and a straightforward mapping?

The possibility that S-R mapping can be bypassed was front and center in the papers originally reporting the absence of an uncertainty effect when the task involved a single, known effector (Kveraga, Boucher, & Hughes, 2002; Lee, Keller, & Heinen, 2005; Wright et al., 2007). These studies suggested that tasks in which responses act on the stimuli that triggered them can bypass S-R mapping. It was precisely this possibility that Wright, Marino, Chubb, and Rose (2011) attempted to undermine by showing that uncertainty effects close to zero can be obtained with spatial indicator stimuli and a straightforward mapping even if the indicator stimulus is spatially distinct from the response target. This question has important theoretical implications for models of S-R mapping and the data that they should explain. For example, Schneider and Anderson (2011) assert a variant of the bypass hypothesis to support their decision not to include the results from these and similar experiments when evaluating their memory based model of Hick's law.

We propose that the S-R mapping process is present, albeit quite fast, in tasks using a spatial indicator stimulus and straightforward mapping of responses. First, as noted above, Wright et al. (2011) have shown that this pattern of results does not require that the indicator stimulus involve a change at the location of the response target; indeed, only small uncertainty effects were observed when (1) the indicator stimulus was a simultaneous change at all of the non-target locations (i.e., the participant had to move to the unique location whose appearance did not change) or (2) the indicator stimulus was an arrow that appeared at fixation pointing to the target. Second, in many of our experiments (including Experiment 1 in this paper) conditions with a straightforward, spatial indicator stimulus yield S-R mapping slopes (b_{SR}^{Spat}) that are small, but discernably different from zero. Finally, there is little evidence, at least for hand movements, that the mapping of visual locations to effective movements to those locations is innate; on the contrary, learning this mapping is one of the important tasks for young infants. These considerations suggest to us that tasks using a spatial indicator stimulus and straightforward mapping of responses include the S-R mapping process; however, extensive practice has made this process very fast (as the studies reviewed by Teichner and Krebs (1974) suggest should be possible) and, as suggested in the Discussion for Experiment 1, it is possible for the slowing due to S-R mapping but not effector selection to approach zero.

Isolating the Effects of Skill

As the argument above suggests, practice is a powerful variable that can influence strongly the size of the uncertainty effects in choice reaction time. Even though the focus of Experiment 1 was not practice *per se*, it did compare performance across levels of practice using sampled variation in typing skill. Because the practice, in this case, did not involve specific practice with the particular tasks studied, it is not surprising that there was credible evidence for a practice effect for only two of the 9 variables in the descriptive model used to summarize the data. These are, however, precisely the two variables that would be expected to be changed by increased touch-typing practice: skilled typists can select more quickly which of several fingers is the movement effector and they more quickly map individual letters onto the appropriate keypress responses. It would be interesting to replicate one of the classic choice reaction time learning experiments (e.g., Hale, 1968) with conditions in which N_A and N_E are not confounded in order to explore whether the effects of practice on S-R mapping and effector selection are linked in any way.

Implications for Models of S-R Mapping in the Context of Hick's Law

There is evidence for four separate mechanisms that each produce choice reaction time effects consistent with Hick's law: i.e., a negatively accelerated function linking the size of observed uncertainty effects with N_A or N_E, which has often been confounded with N_A. For different reasons, in this paper we chose to deemphasize two of these mechanisms, both related to the encoding of the stimulus. The first of these mechanisms has only been shown to occur when the stimulus itself is revealed over an interval ranging from several seconds to 20 seconds or more (Brown, Steyvers, Wagenmakers, 2009). Although this manipulation provides a fascinating window into what would appear to be cognitive decision mechanisms that operate on accumulating evidence, the time scale of this effect moves it outside of the range of phenomena that Newell (1990) called immediate behaviors, which have been our focus here.

The experiments reported by Leite and Ratcliff (2010), which are summarized in the Introduction, illustrate a second of these stimulus-encoding mechanisms in which increases in N_A are associated with a negatively accelerated increase in reaction times. Although the stimulus identification task they studied can be categorized as involving immediate behaviors, we have chosen not to focus on these and other results involving manipulations of stimulus clarity or confusability because the conditions studied led to high error rates, in some cases over 40%. Of course, models that can account for both reaction time and error data have many advantages; however, since most of the papers we are reviewing focus only on reaction time in close-to-error-free performance, we chose to stick with that restriction. Interestingly, we have been unable to find published results that vary both the number of S-R pairings and N_A, and also either stimulus clarity or stimulus confusability while keeping error rates low. Having excluded these uncertainty effects tied to stimulus encoding, we focused on both uncertainty effects attributed to the S-R mapping process and those effects that we have shown to be due to effector selection.

Although other approaches have been considered and largely discarded, at this point in the effort to model uncertainty effects, two types of models dominate: multiple accumulator models (Usher & McClelland, 2001; Usher, Olami, & McClelland, 2002) and the memory model (Schneider & Anderson, 2011). Each approach has advantages and drawbacks. For example, although the original work of Usher and colleagues was largely theoretical, Leite and Ratcliff (2010) reported the results of two studies in which they assessed the ability of several classes of multiple accumulator models to account for not just mean reaction times but also errors, and the reaction time distributions for correct and error responses. However, these efforts did not even acknowledge the large effects of S-R repetitions, nor did they attempt to account for the change of the uncertainty effect size with practice (although clearly these models have the flexibility to be able to incorporate this). By contrast, the memory-based model by Schneider and Anderson (2011) incorporates a mechanism for S-R repetitions (one which we have adopted here), and their evaluation of the memory model provided a demonstration of how it could handle practice effects, and a predicted interaction between N_A, S-R repetitions, and stimulus fan (the number of responses across S-R sets associated with a stimulus), which they then observed in two experiments. However, the memory model does not handle errors or the reaction-time distributions although the authors did discuss how this might be done.

Because neither of these modelling approaches was constructed at a time when there was any suggestion that effector selection might contribute to uncertainty effects, it is not surprising that neither modelling approach includes effector selection or can, in its original form, account well for data in which both N_A and N_E are separately varied. Interestingly, the experiments reported by Leite and Ratcliff (2010) used a task with $N_E = 1$, so their conclusions about S-R mapping do not need to be reconsidered in light of our results. However, because the experiments reported by Schneider and Anderson (2011) to support their claim of the three-way interaction that their model had predicted, confounded N_A and N_E, it is not clear that the source of the interaction is, in fact, S-R mapping.

Perhaps more important than their omission of an effector-selection stage, is that the models of Schneider and Anderson (2011) and Leite and Ratcliffe (2010) could both conceivably be modified to include the influence of effector selection on choice reaction time without altering appreciably the principles advocated in each model to account for S-R mapping effects. So, for example, it seems quite plausible to imagine processes at many levels of neural processing acting like a set of accumulators gathering evidence from a noisy signal until one option reaches either an absolute criterion or a criterion relative to the other possible options. This is one of the attractions of this class of models considered by Leite and Ratcliffe. Models of this type have been proposed for all four of the sources of Hick's-law-like effects except effector selection, and there is no reason to see why the approach could not be applied for effector selection also. It is similarly conceivable that mechanisms grounded in the processes of memory, which Schneider and Anderson (2011) have proposed to provide an account for the uncertainty effect due to S-R mapping, could also work at the level of effector selection. It is less clear how this modelling approach can be used to explain the uncertainty effects associated with stimulus encoding, if as Hawkins et al. suggest this stage operates without an obvious memory component. However, although there is an appeal to the elegance of having all the sources of uncertainty effects arise from a similar mechanism operating separately in different parts of the brain for different stages of the choice reaction process, that in itself is hardly evidence against a memory-based process where it might apply.

Even if the multiple-accumulator and memory-based modelling approaches can be extended to account for the uncertainty effects due to effector selection, it seems likely that these models will have trouble accounting for the new understanding of S-R mapping that must emerge after the uncertainty contributions of effector selection are taken into account. The problem for both models is that they lack a principled way for the proposed mechanisms to account for differences in S-R mapping difficulty other than practice, which has only explicitly been explored by Schneider and Anderson (2011) in the context of their memory model. This is not to deny the very real effect that practice has on the uncertainty slope associated with the S-R mapping function; however, echoing the summaries of research on S-R compatibility (e.g., Kornblum, Hasbroucq, & Osman, 1990), our results in Experiment 1 as well as those of other researchers looking at uncertainty effects (e.g., Dassonville, et al., 1999), suggest that there are differences in S-R mapping difficulty that cannot be ascribed to practice. Although progress has been made in categorizing S-R compatibility effects, the predictions of the models growing out of this research are ordinal (Kornblum et al., 1990). What is needed is a model of the S-R mapping process that simultaneously explains how the time required by the mapping process reflects differences in S-R compatibility. Perhaps, separating the effects of effector-selection from those of S-R mapping will provide the kind of cleaner data that will make this next step possible.

S-R Repetitions

A final observation concerns the importance of analyzing choice reaction time data using models that explicitly account for the nonlinear effects introduced by S-R repetitions. Although concern about the influence of repetitions on choice reaction time data is hardly new) Kornblum, 1973), models that account for these effects have been largely absent from this literature. Although certainly not the only possibility, we found the modeling framework introduced by Schneider and Anderson (2011) worked very well for this. Ignoring repetitions artifactually increases the size of the observed uncertainty effects, and, as Figure 1 illustrates, it does this in a way that depends on the size of the true uncertainty effect. The results from Experiment 1 also show that the hypothesized repetition-bypass mechanism bypasses both S-R mapping and effector selection and that the estimates of the parameters of the repetition-bypass mechanism are stable both within a P across conditions and, somewhat remarkably, across Ps. It would be useful to identify the source of this stability.

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Appendix – Listing of the Stimulus-Response Combinations Used in to Create the Conditions Studied

The entries below show the locations included and the effectors mapped to those locations for each of the 32 unique conditions studied in Experiment 2. If an entry in a grid location is the symbol •, that location plays no role in the condition. Otherwise, the entry will be a two-letter string indicating the effector expected to make the response at that location. The first can be either an L or an R, for the left and right hands, respectively. The second letter can be either an I, M, or R, for the index, middle, and ring fingers, respectively.

Condition=1 Variation=1: $N_A = 1$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

•	•	•		•	•	•
LI	•	•	+	•	•	•
•	•	•		•	•	•

Condition=1 Variation=2: $N_A = 1$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

•	•	•		•	•	•
•	LI	•	+	•	•	•
•	•	•		•	•	•

Condition=1 Variation=3: $N_A = 1$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

•	•	•		•	•	•
•	•	LI	+	•	•	•
•	•	•		•	•	•

Condition=1 Variation=4: $N_A = 1$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

•	•	•		•	•	•
•	•	•	+	RI	•	•
•	•	•		•	•	•

Condition=1 Variation=5: $N_A = 1$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

•	•	•		•	•	•
•	•	•	+	•	RI	•
•	•	•		•	•	•

Condition=1 Variation=6: $N_A = 1$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

●	●	●		●	●	●
●	●	●	+	●	●	RI
●	●	●		●	●	●

Condition=2 Variation=1: $N_A = 2$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

●	●	●		●	●	●
LI	●	LI	+	●	●	●
●	●	●		●	●	●

Condition=2 Variation=2: $N_A = 2$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

●	●	●		●	●	●
●	●	●	+	RI	●	RI
●	●	●		●	●	●

Condition=3 Variation=1: $N_A = 2$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 2$

●	●	●		●	●	●
●	LI	●	+	●	LI	●
●	●	●		●	●	●

Condition=3 Variation=2: $N_A = 2$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 2$

●	●	●		●	●	●
●	RI	●	+	●	RI	●
●	●	●		●	●	●

Condition=4 Variation=1: $N_A = 2$ $N_H = 2$ $N_{F/H} = 1$ $N_S = 2$

●	●	●		●	●	●
●	LI	●	+	●	RI	●
●	●	●		●	●	●

Condition=5 Variation=1: $N_A = 3$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

●	●	●		●	●	●
LI	LI	LI	+	●	●	●
●	●	●		●	●	●

Condition=5 Variation=2: $N_A = 3$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

●	●	●		●	●	●
●	●	●	+	RI	RI	RI
●	●	●		●	●	●

Condition=6 Variation=1: $N_A = 3$ $N_H = 1$ $N_{F/H} = 3$ $N_S = 1$

●	●	●		●	●	●
LR	LM	LI	+	●	●	●
●	●	●		●	●	●

Condition=6 Variation=2: $N_A = 3$ $N_H = 1$ $N_{F/H} = 3$ $N_S = 1$

•	•	•		•	•	•
•	•	•	+	RI	RM	RR
•	•	•		•	•	•

Condition=7 Variation=1: $N_A = 6 \;\; N_H = 1 \; N_{F/H} = 1 \; N_S = 1$

LI	LI	LI		•	•	•
•	•	•	+	•	•	•
LI	LI	LI		•	•	•

Condition=7 Variation=2: $N_A = 6 \;\; N_H = 1 \; N_{F/H} = 1 \; N_S = 1$

•	•	•		RI	RI	RI
•	•	•	+	•	•	•
•	•	•		RI	RI	RI

Condition=8 Variation=1: $N_A = 6 \;\; N_H = 1 \; N_{F/H} = 3 \; N_S = 1$

LR	LM	LI		•	•	•
•	•	•	+	•	•	•
LR	LM	LI		•	•	•

Condition=8 Variation=2: $N_A = 6 \ \ N_H = 1 \ N_{F/H} = 3 \ N_S = 1$

•	•	•		RI	RM	RR
•	•	•	+	•	•	•
•	•	•		RI	RM	RR

Condition=9 Variation=1: $N_A = 6 \ \ N_H = 1 \ N_{F/H} = 1 \ N_S = 2$

•	•	•		•	•	•
LI	LI	LI	+	LI	LI	LI
•	•	•		•	•	•

Condition=9 Variation=2: $N_A = 6 \ \ N_H = 1 \ N_{F/H} = 1 \ N_S = 2$

•	•	•		•	•	•
RI	RI	RI	+	RI	RI	RI
•	•	•		•	•	•

Condition=10 Variation=1: $N_A = 6 \ \ N_H = 2 \ N_{F/H} = 1 \ N_S = 2$

•	•	•		•	•	•
LI	LI	LI	+	RI	RI	RI
•	•	•		•	•	•

Condition=11 Variation=1: $N_A = 6 \ \ N_H = 2 \ N_{F/H} = 3 \ N_S = 2$

•	•	•		•	•	•
LR	LM	LI	+	RI	RM	RR
•	•	•		•	•	•

Condition=12 Variation=1: $N_A = 9$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

LI	LI	LI		●	●	●
LI	LI	LI	+	●	●	●
LI	LI	LI		●	●	●

Condition=12 Variation=2: $N_A = 9$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 1$

●	●	●		RI	RI	RI
●	●	●	+	RI	RI	RI
●	●	●		RI	RI	RI

Condition=13 Variation=1: $N_A = 9$ $N_H = 1$ $N_{F/H} = 3$ $N_S = 1$

LR	LM	LI		●	●	●
LR	LM	LI	+	●	●	●
LR	LM	LI		●	●	●

Condition=13 Variation=2: $N_A = 9$ $N_H = 1$ $N_{F/H} = 3$ $N_S = 1$

●	●	●		RI	RM	RR
●	●	●	+	LR	LM	LI
●	●	●		RI	RM	RR

Condition=14 Variation=1: $N_A = 18$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 2$

LI	LI	LI		LI	LI	LI
LI	LI	LI	+	LI	LI	LI
LI	LI	LI		LI	LI	LI

Condition=14 Variation=2: $N_A = 18$ $N_H = 1$ $N_{F/H} = 1$ $N_S = 2$

RI	RI	RI		RI	RI	RI
RI	RI	RI	+	RI	RI	RI
RI	RI	RI		RI	RI	RI

Condition=15 Variation=1: $N_A = 18$ $N_H = 2$ $N_{F/H} = 1$ $N_S = 2$

LI	LI	LI		RI	RI	RI
LI	LI	LI	+	RI	RI	RI
LI	LI	LI		RI	RI	RI

Condition=16 Variation=1: $N_A = 18$ $N_H = 2$ $N_{F/H} = 3$ $N_S = 2$

LR	LM	LI		LR	LM	LI
LR	LM	LI	+	LR	LM	LI
LR	LM	LI		LR	LM	LI

Endnotes

[i] Lawrence et al. (2008) report data with a negative uncertainty effect for saccades.

[ii] We use this notation, two numbers separated by a ↔, to indicate the range of a 95% confidence interval.

[iii] The natural mapping would associate a target in the left-hand column of the 3 x 3 array to the right of fixation with the index finger on the right. However, in the conditions involving a single finger (on one or both hands), the effector required would be the, possibly less natural, middle finger. However, there were no instances in which the index finger was mistakenly used.