Measuring sequences of keystrokes with jsPsych: reliability of response times and interkeystroke intervals

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Abstract:

While the precision and reliability of response time measurements performed through web-based interfaces has been evaluated, sequences of keystrokes have never been investigated in detail. Keystrokes often occur in much more rapid succession than response times, and operating systems may interpret successive or concomitant keyboard events according to automatic and user-based settings. Sequence keystroke timing could thus be more sensitive than single response times to noise in on-line measurements. Here, we quantified the precision and reliability of timing measures performed during sequences of keystrokes. We used the JavaScript jsPsych library to create an experiment involving finger-movement sequences and run it on-line on 633 participants. We manipulated the structure of three keystrokes motor sequences, targeting a replication of previous findings regarding response times (RT) and inter-keystroke intervals (IKIs). Our on-line data accurately reproduced the original results, and allowed the novel assessment of demographic variables such as age or gender. In parallel, we also measured the objective timing accuracy of the jsPsych interface using specialized hardware and software, showing a constant 60 ms delay for RTs and a 0 ms delay for IKIs across the sequences. The distribution of IKIs revealed quantizing for a majority of participants, most likely due to the sampling frequency of the USB keyboards. Overall, these findings indicate that JsPsych provides good reliability and accuracy in sequence keystroke timing for mental chronometry purposes, through on-line recordings.

Keywords: Interkeystroke intervals; on-line experiment; motor sequence;

Introduction

On-line research via web interfaces is becoming increasingly important in the field of cognitive psychology (Gosling & Mason, 2015). Collecting large amounts of data over hundreds of participants in a short amount of time holds the promise of overcoming the statistical power limitations of typical laboratory samples (Reips, 2002). However, on-line experiments imply a tradeoff between what is gained by dramatic increases in sample size and better sampling of the whole population, and what is lost to uncontrolled factors such as distracting environments and diversity in equipment configurations. The latter is acutely relevant when the experiments rely on mental chronometry (Posner, 1978).

A number of studies have evaluated the accuracy and reliability of response time measurements performed through various web-based interfaces. Such empirical evaluations (reviewed in Reimers & Stewart, 2015) include direct comparisons of experimental results from Web and lab implementations (Reimers & Stewart, 2007; Schubert, Murteira, Collins, & Lopes, 2013), attempts to replicate classical experimental effects on response times with on-line measures (Crump, McDonnell, & Gureckis, 2013; Enochson & Culbertson, 2015; Reimers & Maylor, 2005), and measures of the timing performance of Web-based testing setups using specialist software or hardware (Keller, Gunasekharan, Mayo, & Corley, 2009; Reimers & Stewart, 2015; Simcox & Fiez, 2014). In general, these studies agree that on-line response times are reliable, if slightly overestimated (in the range of tens of milliseconds, de Leeuw & Motz, 2016; Reimers & Stewart, 2007; Schubert et al., 2013).

The studies above have concerned the chronometry of single key presses, with response times (RTs) defined as the time elapsing between the onset of a stimulus and the unitary response. In contrast, tasks involving rapid sequences of keystrokes have never been investigated with on-line setups. Sequences of keystrokes are important for researchers interested in behaviors such as typing, musical performance, motor-sequence learning, serial reaction-time tasks, rhythm production, etc. This line of research is especially interested in the structure of sequence programming and how temporal and ordinal information are acquired during learning, and relates to the general problem of serial order in behavior (for a review see Rhodes, Bullock, Verwey, Averbeck, & Page, 2004). Two dependent variables can be derived from sequences of keystrokes: RTs, defined above, and inter-keystroke intervals (IKIs), the time elapsing between two successive keystrokes. There are two broad reasons why IKIs might be more sensitive than RTs to the noise induced by on-line measurements.

First, IKIs are typically much shorter than RTs. For example, they can last a few tens of milliseconds for expert participants in typing studies (Rumelhart & Norman, 1982), and less than 200 ms for well-trained participants in SRT tasks (Nissen & Bullemer, 1987). A given level of (unavoidable) chronometric imprecision could have a larger impact on the accuracy of such shorter durations than on longer response times. Standard keyboards are connected through USB ports sampled at a rate of 125 Hz (i.e. every 8 milliseconds). Such quantization could distort small differences that happen to be near that range. Crump et al. (2013) and Reimers and Stewart (2015) previously highlighted the difficulties inherent to shorter timings.

Second, we were also concerned that operating systems (OS) settings, such as accessibility features or keyboard hot-keys, might potentially interfere in a detectable way with the recordings and the expected pattern of results. Operating systems interpret successive or concomitant keyboard events according to both automatic and user-based settings (multiple key presses interpreted as one, combinations of key presses triggering a particular event, etc.). The impact of this intermediate layer of software on keyboard chronometry is not known.

There are preliminary indications about how reliably the timing of successive responses can be recorded. Simcox and Fiez (2014) and Keller et al. (2009) used specialized equipment to generate a stream of keystrokes with a fixed known interval. They measured the recovery of such interval through a web-based software, showing good timing accuracy. A limitation of this approach is that their manipulation involved fixed intervals and a single button. A crucial and original feature of the current study is the use of three distinct keys from the keyboard, and the generation of variable delays between keys, just as it happens in actual experiments involving sequence production.

To assess the accuracy of inter-keystroke intervals measured on-line, we adopted a two-fold strategy. First, we measured the timing accuracy of the jsPsych interface using a specialized hardware (Black Box ToolKit) that was modified such that three response switches from the keyboard could be alternatively and variably triggered without human intervention. Second, we ran an actual experiment on-line, and performed a complete quality check of the data using descriptive and inferential statistics.

The experiment we designed involved finger movement sequences for which effects on the recorded RT and the inter-keystroke intervals (IKIs) are well-established (conditions 4 *vs.* 6 of Rosenbaum, Inhoff, & Gordon (1984), experiment 3). In a given block, participants produced two pre-trained sequences of three consecutive finger responses. Across the two sequences, two of the responses are identical whereas the third one is different, which generates an uncertainty. In the original study, response times decreased when the uncertain response occurred later in the sequence. In addition, the IKI preceding the uncertain response was lengthened. These effects of uncertainty on sequence programming and execution have been replicated (Rosenbaum, Hindorff, & Munro, 1987).

Stimulus display and response recording were controlled by the JavaScript library jsPsych combined with HTML and CSS (de Leeuw, 2015). JavaScript offers technical advantages over its alternatives such as Java or Adobe Flash (Reimers & Stewart, 2015). It is natively supported by all modern browsers, such as Firefox or Chrome, and it does not require any installation or updating of browser plugins. This ensures a responsive experimental design and an accurate measurement of response times, as it is not affected by remote server and network latencies. This configuration has been successfully used to record single responses (e.g. de Leeuw & Motz (2016), and other references above).

Hardware assessment of timing accuracy via the *Black Box ToolKit*

Method

Materials and Procedure

To assess the reliability of response times generated by multiple consecutive keystrokes we resorted to a specialized hardware, the Black Box Toolkit (BBTK; Black Box ToolKit Ltd, Sheffield, UK), which can automatically generate and record triggers with sub-millisecond precision. Three mechanical keys (corresponding to the letters S, D and F) of a Dell standard USB keyboard were wired to the Black Box Toolkit. With this wiring, the BBTK was able to close the three key switches on demand and generate keyboard response sequences. In our tests, the BBTK was programmed to detect a visual stimulus through its opto-detector and then automatically generate a sequence of three responses. To handle the display of visual stimuli and the keyboard response collection, we used a jsPsych procedure similar to that used in the actual experimental task (described in the next section and available online: https://github.com/blri/Online_experiments_jsPsych). This procedure was run on iMac 27 using Safari web browser (version 9.0). Three tests were run, all of which consisted in displaying a white letter "@" on a black background 40 times, responded with three keystrokes, thus generating 120 automated keyboard responses. Key identities activated by the BBTK were randomized across and within trials. Programmed response times in the first test were randomly chosen within [100; 250] milliseconds (ms). In the second test, they were fixed at 150 ms. In the third test, the range was [350; 500] ms. Data are available in the following repository: https://osf.io/r5dfg/

Results

Programmed keystroke times were compared to those recorded through the jsPsych procedure. In each of the three tests, the recorded keystroke times (from stimulus to actual keystroke) for each of the three keystroke conditions (first, second and third keystrokes) were all overestimated by about 60 ms (SD = 8 ms; Figure 1, upper panel). This observation was substantiated by an ANOVA with crossed factors keystroke position and test block, in which none of the tests was significant (all p's>0.1). When inter-keystroke intervals were computed (second minus first, and third minus second keystroke times), the difference between programmed and recorded values had a mean value of 0 ms (SD = 10 ms; Figure 1, lower panel). Again, an ANOVA showed no significant effect of position nor test block (all p's>0.1). In short, the first keystroke was recorded with a delay of ~60 ms (probably due to the computation of the stimuli and the physics of LCD screens)[1], and this delay was passed on reliably to subsequent keystrokes. Our measure of primary interest, IKIs, was unbiased, showing a mean error of 0 ms.

1 The delay could occur between the jsPsych pseudo-command “display stim” (where the jsPsych initial clock read occurs) and the actual physical display on the screen (detected by the opto-detector; the BBTK initial clock read). This delay is probably due to the computation of the display screen, the communication between graphic electronic components and the physics of LCD screens, and the timing inaccuracies of jsPsych.

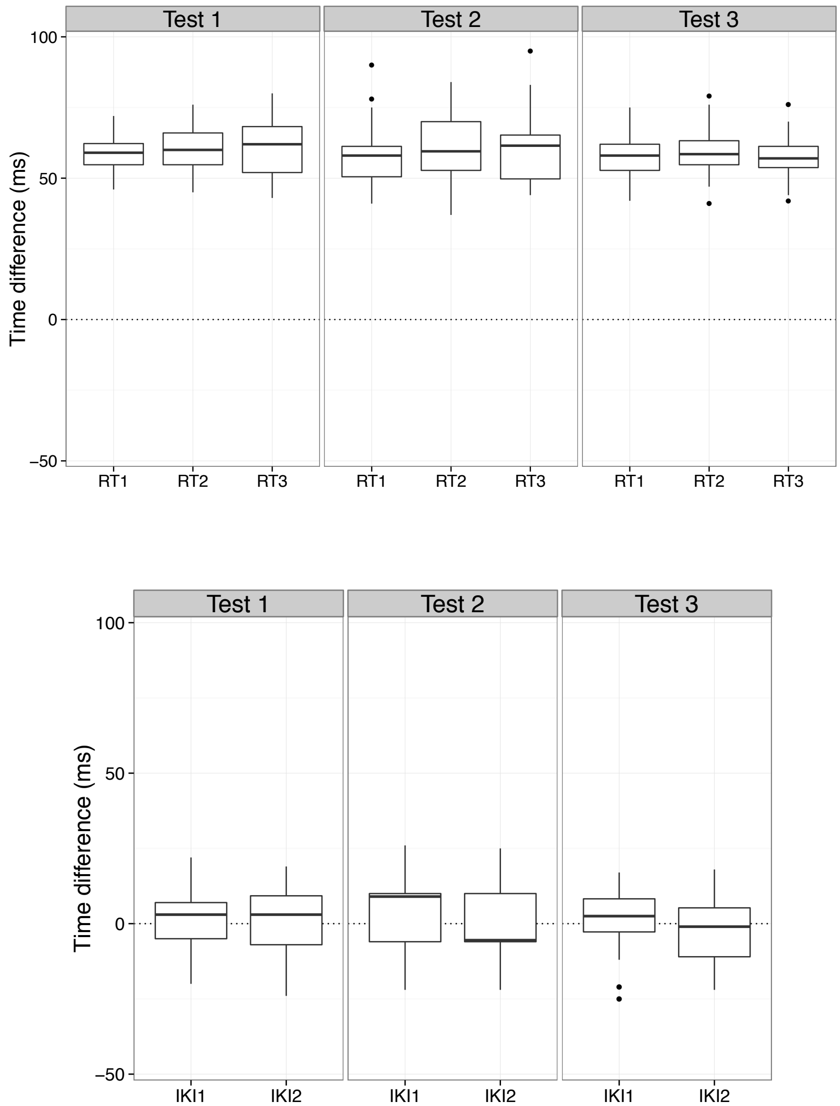
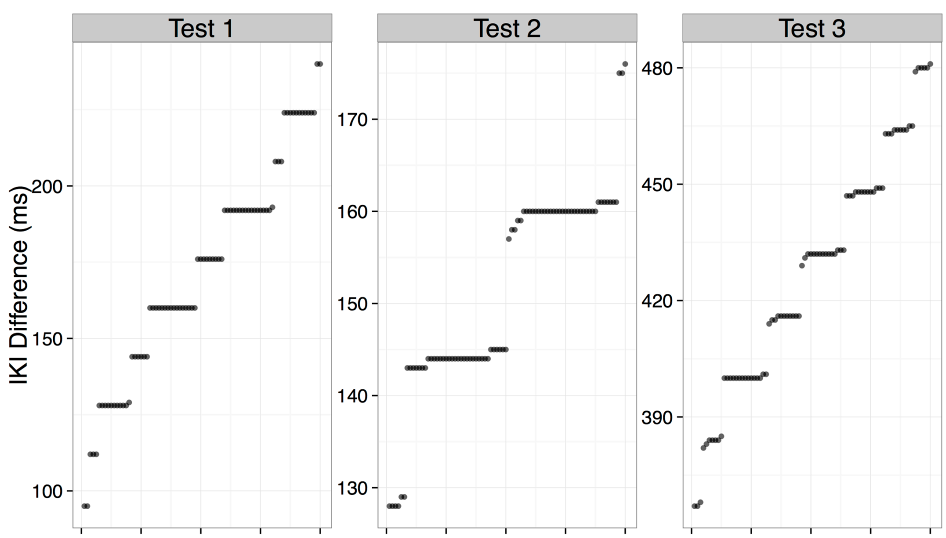


Figure 1. Box-plots (median, 1st and 3rd quartiles, lowest and highest values within 1.5 times the interquartile range) showing the differences between response times recorded by jsPsych and programmed by the BBTK. Top panel: For each of the three tests, the three consecutive response times are RT1, RT2 and RT3. All the conditions had similar distributions centered around 60 ms. Bottom panel: IKIs analysis, similar to RTs. The distributions are centered around 0 ms. Negative values of the difference occur for IKIs when among the two responses used to calculate the actual IKI, the recorded first response is more delayed than the recorded second response.

The variability in the difference between programmed and recorded values, SD = 8 ms, was in the range of the sampling frequency of the USB keyboard (frequency 125 Hz, thus period of 8 ms). This prompted a final analysis to assess the likely quantization of the measure. To show this, we divided each IKI by 8 and took the remainder of the division. If sampling is somewhat biased towards 8, the distribution of the remainder values won't be homogeneous. On the contrary, if sampling happens every millisecond, distribution should be homogeneous. The vast majority of IKIs appears to be multiples of 8, which indeed corresponds to the sampling of the USB connection at 125 Hz (see Figure 2). This quantizing cannot be related to the display of the visual stimulus, since only the onset of the stimulus and therefore the activation of the opto-detector depended on the screen parameters.



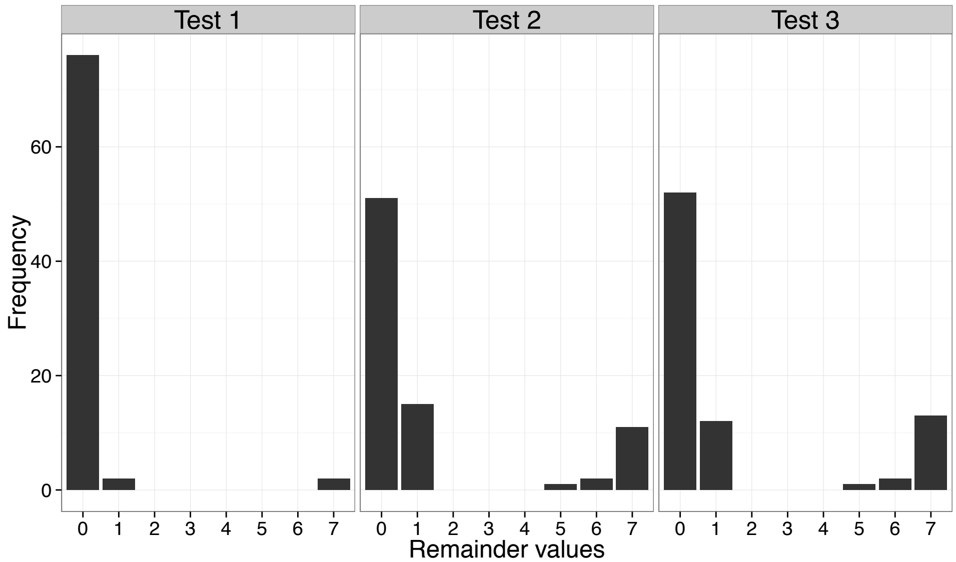


Figure 2. IKIs for the three tests. Upper panel: For each test, IKIs sorted in increasing order are displayed. Lower panel: IKIs values were divided by 8 (in relation to the 125 Hz keyboard sampling rate, see main text for details). The histogram of the remainder values from this division shows that the vast majority of IKIs are multiples of 8.

Discussion

The automatic assessment of sequence keystroke timings generated by the Black Box ToolKit and recorded by a jsPsych procedure revealed that IKIs are unbiased (mean deviation 0 ms) but largely quantized (at 125 Hz, the USB port sampling rate). We now examine how this objective recording conditions fare when attempting to replicate a classic effect on human sequence production.

On-line experiment

The jsPsych platform was used to collect data from a large sample of participants. In order to evaluate the reliability of the jsPysch platform to accurately measure the timing of sequences of keystrokes, we designed a task involving rapid sequences of keystrokes. The overall duration of the task had to be short (less that 20 minutes) paired with easy-to-understand instructions to be adapted to an on-line format. Therefore, we aimed to reproduce two classic effects on motor sequence performance with a design adapted from Experiment 3, conditions 4 *vs.* 6, of Rosenbaum, Inhoff, & Gordon (1984). From the original design we selected only two conditions to show differences between RTs and IKIs related to the structure of the sequence performed while keeping the duration of the experiment as short as possible. The conditions were the most different in terms of the sequences used (different hand and finger, see below) and yielded the largest difference in RT and IKI measures. The original study explored the motor representations used to perform sequences in a choice-reaction-time task design, where participants had to select a sequence of motor responses to a visual stimulus (X or O). In the original experiment, the sequences had three finger responses that differed by one element placed either on position 2 or on position 3. The variable element involves both a change of hand and the choice of a non-homologous finger (e.g., R-Ring to L-Index). Rosenbaum et al. (1984) found that the position of the uncertain response had an effect on RTs, with longer RTs for uncertain responses in position 2 than in position 3 (with means of about 460 and 380 ms; data from Rosenbaum et al., 1984). In addition, the IKI preceding the uncertain response was found to be longer, as attested by a significant interaction between the position of the uncertainty and the position of the required response (with mean IKI1 uncertain = 193 ms; mean IKI1 certain = 177 ms; mean IKI2 uncertain = 233 ms; mean IKI2 certain = 163 ms; data from Rosenbaum et al., 1984). The original experiment involved 6 participants.

Method

Participants

Members of our university staff were invited by email to participate to the online experiment. After 31 days, we had collected data from over 600 participants (100 times more than the original), and data collection was discontinued. Ninety-two participants were excluded, mainly based on self-reported technical or concentration issues, leaving a usable sample of 541 participants. Reported issues ranged from interruption during the task (17), difficulty to understand instructions or to stay focused (20), discomfort during task (13), troubles with their specific devices (e.g., keyboard; 11), and various other issues (26). Any participant who reported an issue (whether specific or not), or was below 18 years of age was excluded from the final participant pool. Table 1 outlines the demographics of the final sample. We also collected information about OS and web browsers used (Table 2). The most frequent combination was Windows and Firefox.

Table 1. Sample characteristics

Handedness	471 right	69 left
Gender	324 women	214 male
Age	mean= 39.64, median = 39, Q1-Q3 = 30-47, range = 21-69	
Affiliation	228 work at AMU, 21 study at AMU, 19 unrelated, 273 not specified	

Table 2. Web browsers and OS sample characteristics

	Linux	OS X	Windows
Firefox	27	54	254
Chrome	4	18	80
Explorer	0	0	51

Safari	0	45	0
Other	6	0	1

Stimuli and design

The design is summarized in Table 3. The two constant sequences were unimanual and consisted of the sequence [Index, Ring, Middle fingers], either performed with the left or right hand (factor hand). Four varying sequences comprised a variation from the constant sequences on either the second or third position (factor uncertainty). A block contained two interleaved sequences, one constant and one varying. Each subject was assigned randomly to one constant sequence (thus to one level of the factor hand, IRM or irm, see Table 3) and performed the two uncertainty conditions (2nd and 3rd) for his/her assigned hand in consecutive blocks. The association of a given sequence with visual stimulus (X or O) and the order of presentation of Uncertainty conditions were randomized across subjects.

Table 3. Design table. Lower case letters correspond to left-hand fingers, upper case letters to right-hand fingers. I: index; R: ring; M; middle.

Sequence	Uncertainty	Hand	
		Left	Right
Constant	-	irm	IRM
Varying	2nd	iIm	IiM
	3rd	irI	IRi

Procedure

The on-line experiment consisted of a set of HTML, JavaScript, CSS and PHP files. These files were stored on a server that was already set up and managed by Sebastiaan Mathôt (co-author of this study), and associated with the *cogsci.nl* domain name. The collected data were saved in the mySQL database that was configured on this server machine.

The experiment itself was mainly developed using the open-source jsPsych library (v4.3 2015;de Leeuw, 2015). This library contains predefined methods to manage the experiment timeline, collect reaction times and user actions (mouse, keyboard events), randomize stimuli, store the data, and prepare data for the backup. A plugin was devoted to the main task of the study, involving the typing of a three-key sequence following a visual stimulus (i.e. a character appearing on the screen). This plugin, called *jspsych-key-sequence*, allowed recording the typing times of each pressed key through an adaptation of an available jsPsych plugin (*jspsych-multi-stim-multi-response*). Collection of each keystroke timing relied on the jsPsych method getKeyboardResponse(), which uses the general JavaScript object Date(). The visual stimulus, the corresponding expected typing sequences, the total number of stimulus and the inter-stimulus duration were configurable as input parameters and were adapted for the blackbox testing. When given several types of stimuli and associated sequences, the stimuli were first randomly shuffled to be displayed successively. The code for this experiment is available in the following GitHub repository: https://github.com/blri/Online_experiments_jsPsych. The on-line experiment started with a welcome screen containing concise explanations. Within this web page, a push button only visible to a computer-based browser allowed the participant to go further; this way, participants using tablets or smartphones were automatically excluded from the experiment. A second web page was then loaded in a full-size window, which embedded the javascripts (jsPsych core script and plugins, jQuery) necessary to launch the experiment.

The experiment was divided into two parts, one for each uncertainty condition; each part comprised a training phase and a test phase. Written instructions described the task and introduced the pairing between visual stimuli (X and O) and sequences for each part. During the test phase, one of the two visual stimuli was displayed and stayed on until the participant hit three keys, followed by an interval of 500 ms. The test phase comprised two blocks of twenty trials each, in which ten trials of each sequence were intermixed. Participants were familiarized with the sequences during a training phase, which ended when each sequence was correctly performed 4 times. Before the test, the plugin was set in a training mode that could be switched on from the input settings, and allowed to provide feedback by changing the color of the stimulus before it disappeared (the initially black symbol became green if the key-sequence was correct, red otherwise). After the experiment, participants were asked to answer a few questions (handedness, gender, age, employed by university or else) and had the opportunity to report if any problem occurred during the experiment. There was no monetary compensation offered.

Before launching the large-scale study, the on-line experiment was pre-tested on a small number of participants (N = 54), in order to assess the clarity of the instructions and the functioning of the program in various material configurations. A spy library was included in the experiment file, sending us the JavaScript error message encountered by any user's browser (https://github.com/posabsolute/jQuery-Error-Handler-Plugin). Five errors were reported due to four JavaScript methods that were not interpreted by old browser versions. To avoid subsequent errors, a polyfill was added to the experiment file (see code in the dedicated GitHub repository).

Data related to the experimental task comprised keys of sequences, associated typing times and survey answers. They were recorded as a JavaScript object during the experiment, that was subsequently transformed in plain text before being sent to the server. At the end of each experiment, the data were transferred to the server as character arrays, including the participant anonymous identifier, OS/browser information, and the jsPsych data. The transferred dataset was finally stored in the MySQL database by the help of PHP files. The access to the database and the writing of the data inside the data table were done using PHP Data Object (PDO) extension, which ensured database portability and security.

Data are available in the following repository: https://osf.io/r5dfg/

Statistical analyses

To replicate the original study, the data were first assessed via ANOVAs performed on RTs and IKIs averaged per participant and cell design. Then, mixed linear regressions were used to estimate actual effect sizes, also for the effects of additional variables: trial number, gender, age, handedness, OS and web browser. These variables were tested as linear predictors, except for age. The relation between age and performance has been reported as non-linear (Baltes & Lindenberger, 1997) and spline interpolation has been successfully used in cognitive aging research to approximate age effect trajectory (Fozard, Vercruyssen, Reynolds, Hancock, & Quilter, 1994). Visual inspection of our data suggested that the effects of age on performance (RT) could be non-linear. Therefore, we used restricted cubic splines with three knots, which allows the effect to be modeled separately in two intervals, without *a priori* about the point of separation between these intervals. In the model, we included random intercepts for participants and items (i.e. the different finger sequences). Since computing p-values in this kind of analysis is debated (Bates, Mächler, Bolker, & Walker, 2015), we took t-values to approximate z-values, and considered any value above 1.96 significant.

To characterize data reliability, and the added value of increasing the number of observations, we calculated the mean and confidence intervals of RT and IKI over random samples of increasing size, then ran the same regression models on samples of increasing size.

Finally, based on the results of the BBTK assessment, we searched for quantization in our data. We focused mainly on sampling bias that could result from USB keyboards sampling rate (125 Hz, i.e. a value being sampled every 8 ms) and used the same methodology as reported above.

Results

1. Replication of original study

RT & IKI distributions

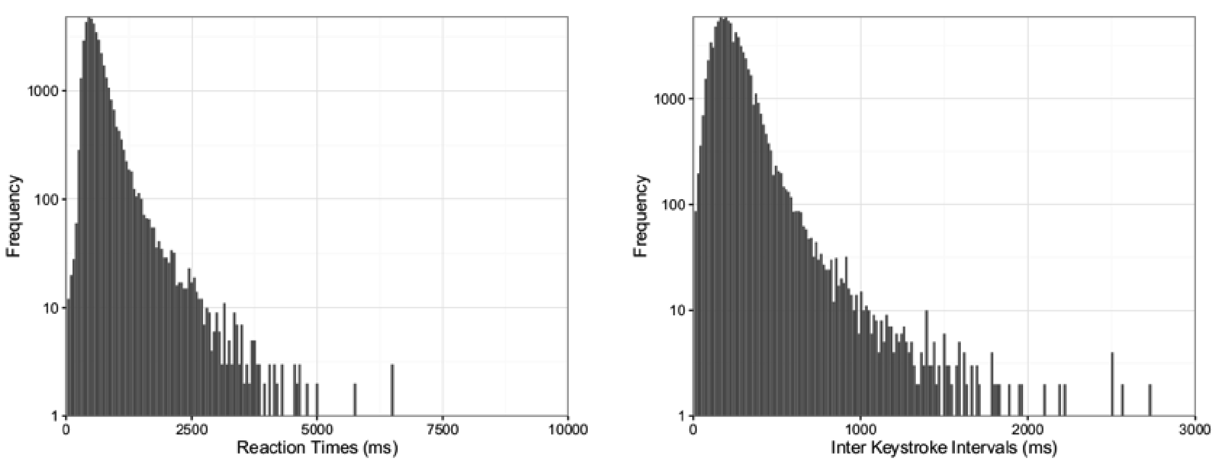


Figure 3. Distributions of reaction times and interkeystroke intervals for correct trials. Y-axis is log-transformed. Three very extreme values (46.4 s, 153 s, 174 s) were removed from the RT distribution for display purposes.

Twelve out of the sample of 541 participants were excluded because they did not reach 85 % accuracy on the task, leaving a final sample of 529 participants. Only correct trials are included in the following analysis. We also excluded trials in which any IKI was equal to zero, as the order of key pressing can't be determined.

Figure 3 presents RT and IKI distributions of correct responses, right-skewed as expected (Skewness RT = 117.1; Skewness IKI = 5.46). The shape of the IKI distribution was also consistent with the typically described shape of IKIs distribution from laboratory studies of typing, less right-skewed than typical RT distributions (e.g., Gentner, 1983). No deadline was imposed during the course of a trial, and a few very extreme values were recorded. In order to study the processes of interest, we choose a 3000 ms high cut-off for RT to identify trials where participants were actively engaged in the task. Based on rough approximations of neural conduction time, we considered RTs below 200 ms to be anticipations not directly triggered by to stimulus presentation, and excluded those trials. These cut-offs on RT have very little effect on IKI distribution (0.57% of data removed). Similarly, to study trials in which participants were engaged in the task for the whole course of the trial, we kept trials with IKI lower than 1000 ms. This whole procedure left 92.5 % of the data.

Effects of uncertainty on RT and IKI

For RTs, the design included the following factors: position of *Uncertainty* (on 2nd or 3rd keystroke), type of *Sequence* (Constant or Varying) and *Hand* of the constant sequence (Left or Right). We did not include any interaction between Hand and the other factors in the design. An ANOVA revealed a main effect of Uncertainty ($F(1,528) = 373$, $p < 0.001$); RTs were shorter for sequences varying on the 3rd than on the

2nd key (M2nd = 677 ms; M3rd = 560 ms). This is in good agreement with the original results of Rosenbaum et al. (1984). The main effect of Sequence also reached significance ($F(1,528) = 187$, $p < 0.001$); RTs were shorter for constant sequences (Mc = 597 ms; Mv = 640 ms). Finally, the Sequence x Uncertainty interaction was also significant ($F(1,528) = 7.3$, $p < 0.01$). The main effect of Hand was not significant ($F < 1$).

For IKIs, the design was similar with the additional factor *Position* of the interval within the sequence (1^{st} or 2^{nd} IKI). An ANOVA revealed main effects of Sequence ($F(1,528) = 37$, $p < 0.001$) and Position ($F(1,528) = 7.4$, $p < 0.01$); IKIs were overall shorter in varying than in constant sequences (Mv = 221 ms, Mc = 228 ms); they were also shorter at the second than at the first position ($M2^{nd}$ = 222 ms, $M1^{st}$ = 227 ms). The interactions Sequence x Position ($F(1,528) = 68.8$, $p < 0.001$), Sequence x Uncertainty ($F(1,528) = 5.0$, $p < 0.05$), and the two-way interaction of Sequence x Uncertainty x Position ($F(1,528) = 27.6$, $p < 0.001$) were also significant. Crucially, the interaction Uncertainty x Position was highly significant ($F(1,528) = 191$, $p < 001$), indicating that IKI was longer at position of uncertainty (Figure 4). The interaction of Uncertainty x Position was robust, also observed on subsets of the data (see supplementary material for operating systems Windows and OS X and web browsers Chrome and Firefox). In short, the ANOVA analysis revealed that the main results from the original study were replicated.

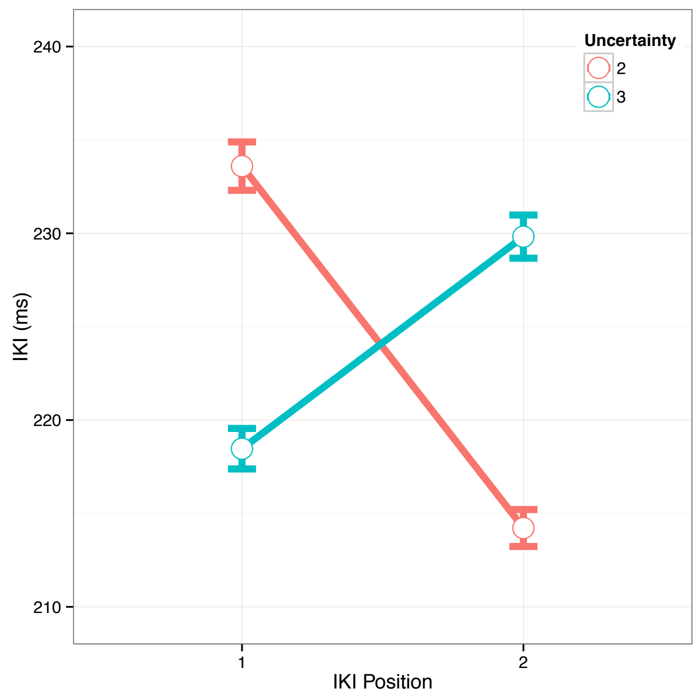


Figure 4. Mean IKI as a function of Uncertainty (on 2nd or 3rd element of the sequence) and Position within the sequence (first or second). Error bars represent mean standard error estimated by bootstrap.

Effects of participant characteristics on RTs and IKIs

We also used regression to better estimate effect sizes over and above individual characteristics (participants and computer configurations; Tables 4 and 5). The contrasts in categorical variables were assessed against the most frequent category (Windows operating system and Firefox web browser).

Summarizing the results on RTs (see Table 4), we obtained the same significant effects as with the original ANOVA, although the Sequence x Uncertainty interaction did not reach significance and presented a small estimate. Importantly, the estimates for the main effects of Sequence and Uncertainty were the largest. Regarding IKIs (see Table 5), all main effects and interactions reached significance, except the main effect of Hand. Our interaction of interest Position x Uncertainty presented one of the largest estimates.

Introducing personal characteristics in the model yielded a significant main effect of Gender, with male participants being faster than female participants both for RTs and IKIs. We also observed a slight slowing down of both RT and IKI with age but no significant effect of handedness (Tables 4 and 5). Regarding computer configurations, only the contrast of Chrome against Firefox on RT approached significance, with responses collected from Chrome being faster (see supplementary material). This contrast did not reach significance on IKI.

Table 4. Mixed model regression coefficient for RTs.

	ß	SE	*t*	95% CI	*(sig.)*
(Intercept)	592.55	57.09	10.38		
Experimental variables					
Hand	-5.87	13.66	-0.43	[-32.69; 20.96]	
Sequence	46.71	5.43	8.61	[36.05; 57.37]	*
Uncertainty	-116.48	3.34	-34.90	[-123.04; -109.92]	*
Sequence x Uncertainty	-11.75	6.36	-1.85	[-24.24; 0.74]	
Trial number	-1.05	0.03	-31.65	[-1.11; -0.98]	*
Subjects' variables					
Gender	-54.32	13.78	-3.94	[-81.38; -27.26]	*
Age (spline 1)	3.50	1.64	2.13	[0.27; 6.73]	*
Age (spline 2)	3.94	2.07	1.90	[-0.13; 8.01]	
Handedness	25.51	19.53	1.31	[-12.85; 63.87]	
Computers' variables					
OS: OS X/Windows	4.19	19.95	0.21	[-35; 43.37]	
OS: Linux/Windows	-45.02	28.72	-1.57	[-101.43; 11.39]	
Web Browser: Chrome/Firefox	-55.77	17.51	-3.19	[-90.16; -21.38]	*
Web Browser: IE/Firefox	27.45	23.23	1.18	[-18.19; 73.09]	
Web Browser: Safari/Firefox	-50.50	29.71	-1.70	[-108.86; 7.86]	
Web Browser: Autres/Firefox	36.51	62.11	0.59	[-85.5; 158.53]	

Table 5. Mixed model regression coefficients for IKIs.

	ß	SE	*t*	95% CI	*(sig.)*
(Intercept)	205.14	26.11	7.86		
Experimental variables					
Hand	-8.16	6.13	-1.33	[-20.21; 3.89]	
Sequence	-21.18	1.65	-12.84	[-24.42; -17.94]	*
Uncertainty	-23.13	1.06	-21.91	[-25.2; -21.05]	*
Position	-30.81	1.06	-29.18	[-32.89; -28.74]	*
Sequence x Uncertainty	12.93	1.95	6.62	[9.09; 16.77]	*
Sequence x Position	22.71	1.49	15.22	[19.78; 25.64]	*
Uncertainty x Position	39.30	1.49	26.37	[36.38; 42.23]	*
Sequence x Uncertainty x Position	-17.94	2.10	-8.53	[-22.07; -13.81]	*
Trial number	-0.28	0.01	-37.89	[-0.3; -0.27]	*
Subjects' variables					
Gender	-35.56	6.32	-5.63	[-47.97; -23.16]	*
Age (spline 1)	1.46	0.75	1.94	[-0.02; 2.94]	
Age (spline 2)	2.44	0.95	2.57	[0.58; 4.31]	*
Handedness	9.41	8.95	1.05	[-8.18; 26.99]	
Computers' variables					
OS: OS X/Windows	-1.50	9.14	-0.16	[-19.46; 16.47]	
OS: Linux/Windows	-5.40	13.16	-0.41	[-31.26; 20.46]	
Web Browser: Chrome/Firefox	-0.68	8.02	-0.08	[-16.44; 15.09]	
Web Browser: IE/Firefox	1.78	10.65	0.17	[-19.14; 22.7]	
Web Browser: Safari/Firefox	0.18	13.62	0.01	[-26.58; 26.93]	
Web Browser: Autres/Firefox	1.63	28.48	0.06	[-54.32; 57.57]	

2. Additional analyses

Having reproduced the result from Rosenbaum et al. (1984), we aimed to further characterize the data collected via the on-line platform.

Estimation of data quantization

Similar to the analyses performed on the hardware test data above, we evaluated the extent of data quantization in the on-line experiment. To this end, IKIs were sorted in increasing order. Figure 5 (upper panel) displays two representative subjects: IKIs for the subject on the left panel take almost all possible values between 130 and 190 ms; in contrast, IKIs for the subject on the right panel are concentrated around multiples of 8.

This sampling bias was assessed on transformed IKI distributions, generated by taking the remainder values from the division by 8. The homogeneity of these distributions was quantified over the whole sample with independent chi-square tests for each subject (see Method section), which revealed that 449 subjects (83% of the sample) presented a sampling bias (as indexed by significant chi-square tests, FDR-corrected). This confirms that we should not expect a precision higher than 8 ms on actual IKI measurements. The reason why some the data from some participants did not show this quantization could not be meaningfully traced to the specific features of their computer configurations that were available to us.

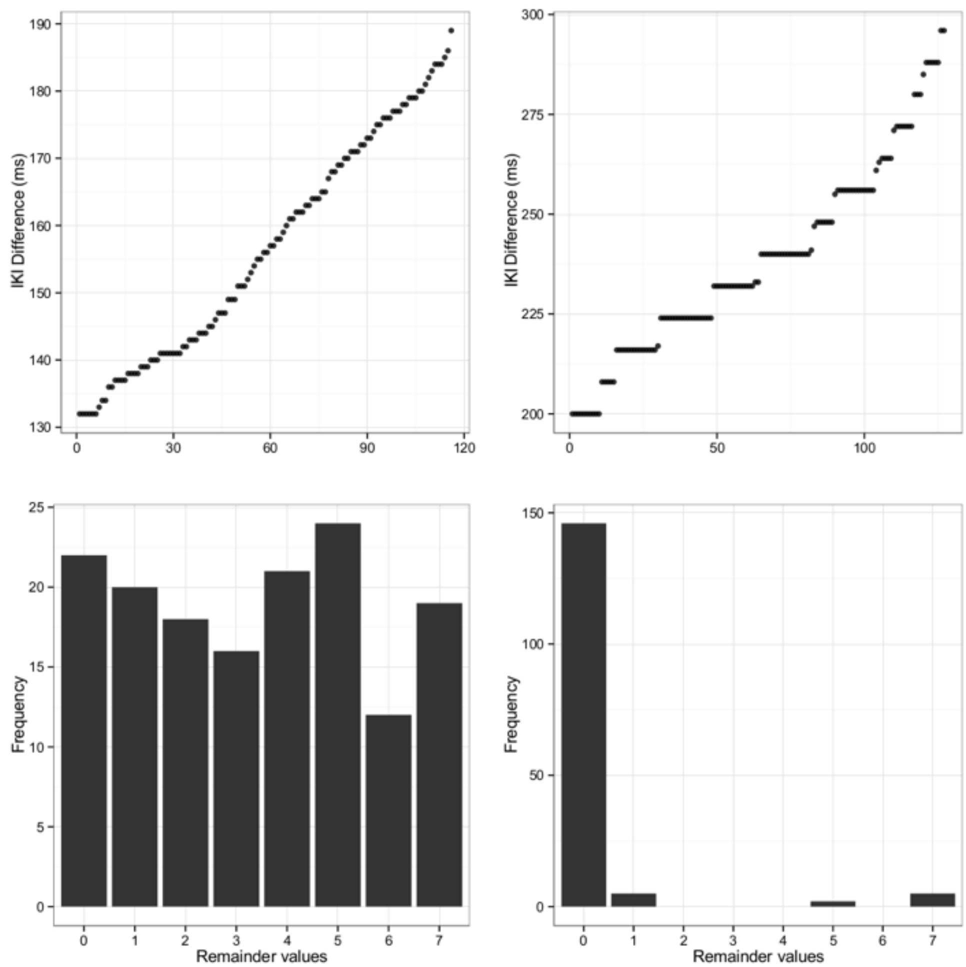


Figure 5. Data sampling of two representative subjects (left and right columns). Upper row represents IKIs, ranked in increasing order. Lower row represents the distribution of the remainders from the division of IKIs by 8. The data on the right show quantization around multiples of 8 (see main text for details).

Data reliability

There were only 6 participants in Rosenbaum's original study. Our final sample size (N = 541) allowed us to assess the relationship between sample size and effect reliability. From the data, we randomly selected samples from 6 to 100 subjects (with replacement). For each sample size, 20 samples were drawn from the original distribution and we calculated the mean (RT or IKI) and estimated the confidence interval of each sample. As sample size increases, the sample means are getting less dispersed around the mean of the whole distribution and the range of the confidence intervals decreases: the sample means become more stable estimates of the mean of the whole sample (Figure 6A).

To evaluate the effect of sample size on the experimental effects, we followed the same procedure, taking random samples of increasing size from the whole distribution and running the mixed regression model described above on each sample. Figure 6B presents the evolution of the beta estimate for the interaction Uncertainty x Position across samples. It shows that the effects are well estimated from a sample size of 50, as from this value and above, all the confidence intervals include the mean of the whole distribution.

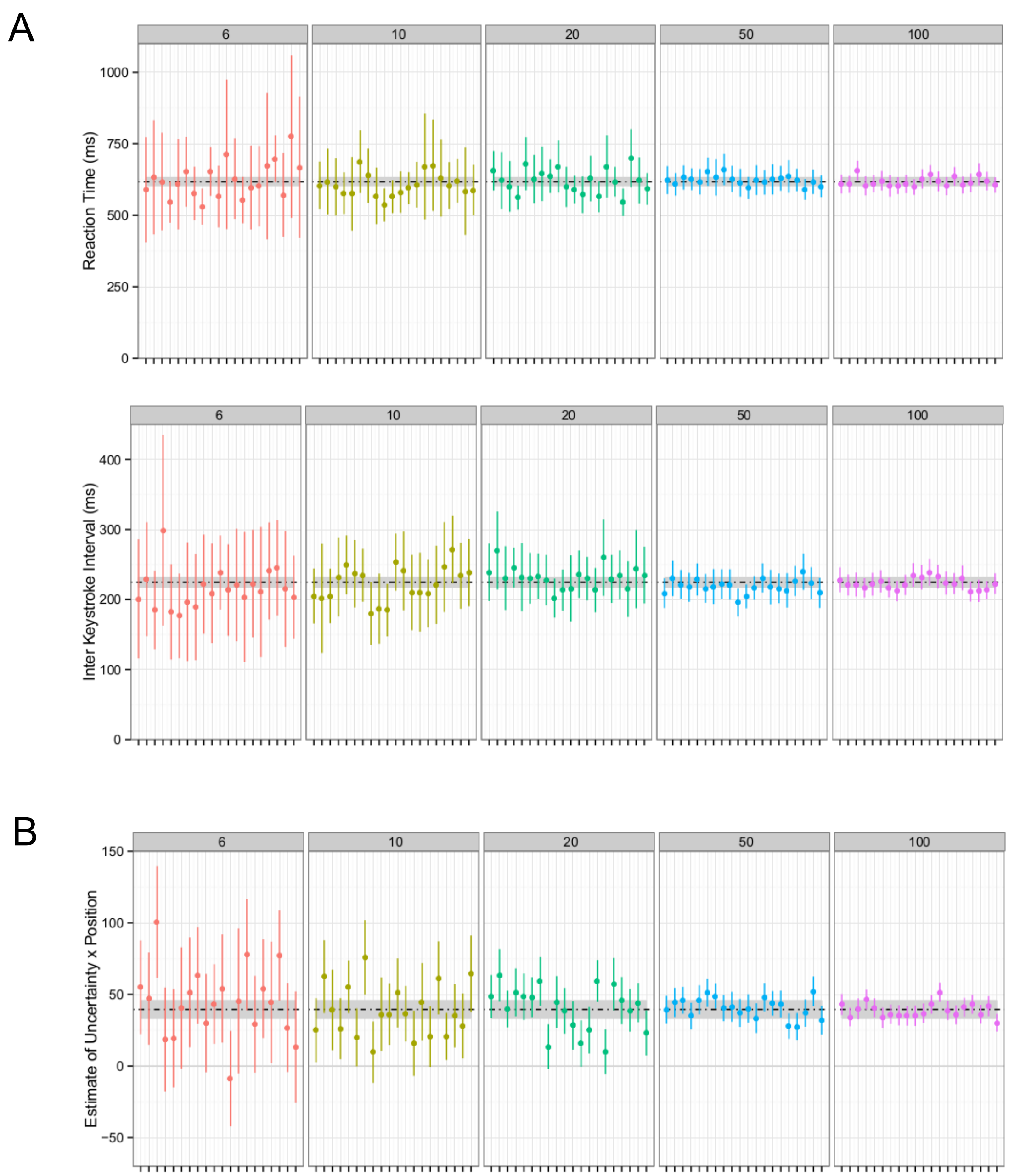


Figure 6. (A) Mean and confidence intervals of RT (top) and IKI (bottom) over random samples of increasing size (see text for details). The horizontal line represents the mean of the whole sample with confidence intervals as a surrounding shaded area. Each point represents a random sample, sample size is indicated above each panel. (B) Beta estimates and confidence intervals for the interaction Uncertainty x

Position evaluated in mixed regression models on IKI over random samples of increasing size. The horizontal line represents the beta estimate from the model on the whole sample (reported in Table 5) with confidence intervals as a surrounding shaded area.

General discussion

We aimed at quantifying the precision and reliability of timing measures performed during sequences of keystrokes. We used the JavaScript jsPsych library to create an experiment involving finger-movement sequences. The Black Box Toolkit (BBTK) hardware tests showed a systematic delay centered around 60 ms for RTs and an unbiased measure with average 0 ms delay for IKIs. Thus, the delay in response-time measurements did not increase when several keystrokes were collected in rapid succession. Then, the on-line experimental data accurately reproduced the original results (Rosenbaum et al., 1984). Random subsampling of the data revealed that, in paradigms such as this, samples of at least 50 participants are necessary for accurate estimation of data distributions and experimental effects. Finally, both BBTK tests and on-line experiment revealed substantial quantizing of the IKI data, most likely due to the sampling frequency of the USB keyboards (125 Hz). This did not prevent the assessment of experimental effects with reasonable sample sizes.

The finding of a null difference between programmed and recorded IKIs with the BBTK is a good indication that on-line testing can be used for assessing differences in the timing between elements of motor sequences performed through the keyboard. It generalizes the findings of previous experiments that used a stream of identical keystrokes separated by fixed intervals in comparable conditions (Keller et al., 2009; Simcox & Fiez, 2014). Here, we measured a sequence of responses to a visual signal, with variable inter-response intervals. In addition, we showed that even for short time-intervals, the on-line system performs with a very good timing precision. Standard deviations for the IKIs were very small (around 10 ms), a value that is considered accurate in response time measurements (see Reimers & Stewart, 2007, 2015). The BBTK tests therefore also indicate a good reliability of the measures.

The BBTK tests revealed a constant lag of about 60 ms on the RT measurements using our jsPsych configuration. The finding of a lag is consistent with another study who compared jsPsych with programs designed for in-lab recordings (de Leeuw & Motz, 2016). Comparable amounts of overestimation of RTs were also observed by Reimers and Stewart (2015) in a test with the BBTK and JavaScript, so in a design very similar to ours except for the motor-sequence feature and the use of predefined jsPsych methods. Those authors tested various browsers and OS-es with the BBTK, on JavaScript and html5, and showed a general overestimation of RTs varying from 30ms to nearly 100 ms (on a Dell Optiplex machine). Some operating systems seem to introduce longer lags; for instance, in their experiment the two Windows 7 machines measured response times that were 30–40 ms longer than the XP machines. In our case, the delay between programmed and recorded responses is probably a mixture between the load of ongoing programs running in the operating system, hardware constraints (Safari browser and Macintosh computer) and the jsPsych program itself. In addition, a standard deviation of 8 ms is a small value, similar to that of Reimers and Stewart (2007; 2015) for measures of RTs. Based on those SD values, those authors, by comparing on-line and traditional measures, acknowledged that on-line measures overestimate RT but do not add extra noise to the data. Relative to the recording of keystroke timings using a JavaScript implementation relying on the "Date" object, the present use of the getKeyboardResponse() jsPsych function could possibly add a small processing overhead[2]. If this overhead impacts the recording of keystroke timings, this impact is likely to be very small since our values are very close to those of Reimers and Stewart (2015). This supports the generalizability of the present findings to any JavaScript experiment beyond jsPsych. In addition, this indicates that JsPsych can be used by researchers in experimental psychology who need to implement experiments with high timing precision.

[2] Due to the addition of two if statements linked to the parameterization of the function. Time measurements themselves are done basically by instantiating JavaScript Date objects. In addition, profilers indicate that the overall execution time of getKeyboardResponse(), including the definition of start_time, key_time and associated conditions, ranges between 3.4 and 5.5 ms (using Chrome DevTools and Firebug profiling respectively).

Quantizing of the IKIs occurred for all the three BBTK tests, and for the on-line measurements. A similar phenomenon has also been shown by Neath, Earle, Hallett, & Surprenant (2011), when testing various configuration of program/computer and keyboard. There, quantizing occurred only occasionally, and seemed to be related to one particular configuration of a given MacIntosh computer and a particular type of keyboard, and was not discussed further. Quantizing of the responses was also observed by Reimers and Stewart (2015) based on cumulative frequency distributions. Quantizing occurred more frequently under certain configurations, but the authors could not find any systematic predictor of quantizing in the data. Here, in addition to showing quantizing as usual with cumulative frequency distributions, we used a procedure that allowed the quantification of the intervals between which data were sampled. In the BBTK tests, data were "packed" by multiples of 8 ms, a value that corresponds well to the sampling rate of an USB port (125 Hz). This was also the case in data recorded on-line with actual participants and variable computer settings. A great majority of the sample displayed the same quantizing by steps of multiples of 8 ms. This is a strong suggestion that quantizing is due to the sampling of the keyboard by the system. Such non-continuous sampling of the data should be acknowledged, and some researchers for whom quantizing matters have to be aware of it and choose non-USB input devices. However, a specific study shows that under typical response time measurements conditions, the variability in human performance outweighs the imprecision in response devices (Damian, 2010).

Our on-line study on a large sample of participants also replicated the original results of Rosenbaum et al. (1984): the position of the uncertain response had an effect on RTs, with longer RTs for uncertain responses in position 2 than in position 3. In addition, we found the same interaction between the position of the uncertainty and the position of the required response on IKI measurements. The main effect of Uncertainty reported in the original experiment did not reach significance in our sample, while the other effects we reported were not significant in the original study. This discrepancy is probably related to the instability of the effects estimated by Rosenbaum et al. in the original study. The interaction of interest has been replicated later on (Rosenbaum et al., 1987) and can be considered reliable. It should nonetheless be kept in mind that the original effects were reported on a sample of only 6 participants. In regard to our specific conditions (e.g., same number of trials as in the original study but only a subset of the original experimental conditions), and experimental context (on-line measurements), we found that a minimum sample size of 50 subjects was necessary to provide a relatively good and reliable estimation of the effect of interest. This threshold is nonetheless specific to the present experiment and clearly not a recommendation for a minimum sample size in any on-line experiment as its value is likely to depend on a number of factors such as the number of trials and effect sizes. Our analysis nonetheless provides an illustration of the tradeoff between sample size and the precision of the estimate of effects of interest that depends on the constraints of a given experiment. Systematic tests of this type in methodological or experimental on-line studies would be useful to get a better overview of the minimally required sample sizes in various contexts.

Our measured RTs were longer than in Rosenbaum et al.'s study: this could be due to the time lag (as measured with the BBTK) introduced by the operating system, computer, screen and keyboard used (see Neath et al. (2011) for example for the keyboard), as well as the on-line configuration of the browser and jsPsych. This finding is in agreement with previous studies that compared in-lab and web-based experiments and typically found delay from 25 to 100 ms (Crump et al., 2013; de Leeuw & Motz, 2016; Reimers & Stewart, 2007; Schubert et al., 2013).

Regression analyses also indicated that the material configuration proved no measurable effect on IKIs, although an effect of browser was evidenced for RTs. Moreover, our on-line interface could capture some variability linked to demographic variables: for instance, it allowed the extra assessment of the effect of variables such as age or gender. We found a slight influence of age and gender on both RTs and IKIs. Previously, no effect of age has been reported on typing rate (Salthouse, 1984) or indirect measures of motor sequence learning (Howard & Howard, 1989). However, a male advantage on motor speed has been reported (Nicholson & Kimura, 1996). Such effects should be taken cautiously, as predictors such as age, gender and computer configurations might be correlated, as suggested by Reimers and Stewart (2015), and lead to spurious effects of covariates. Mixed regression analyses then present the advantage to account for all predictors and their specific variability at the same time.

In conclusion, the on-line measurement using jsPsych appears an accurate way to test for fine differences between inter-keystroke intervals (IKIs) in various conditions. It offers a promising tool for researchers interested in motor sequence learning and execution.

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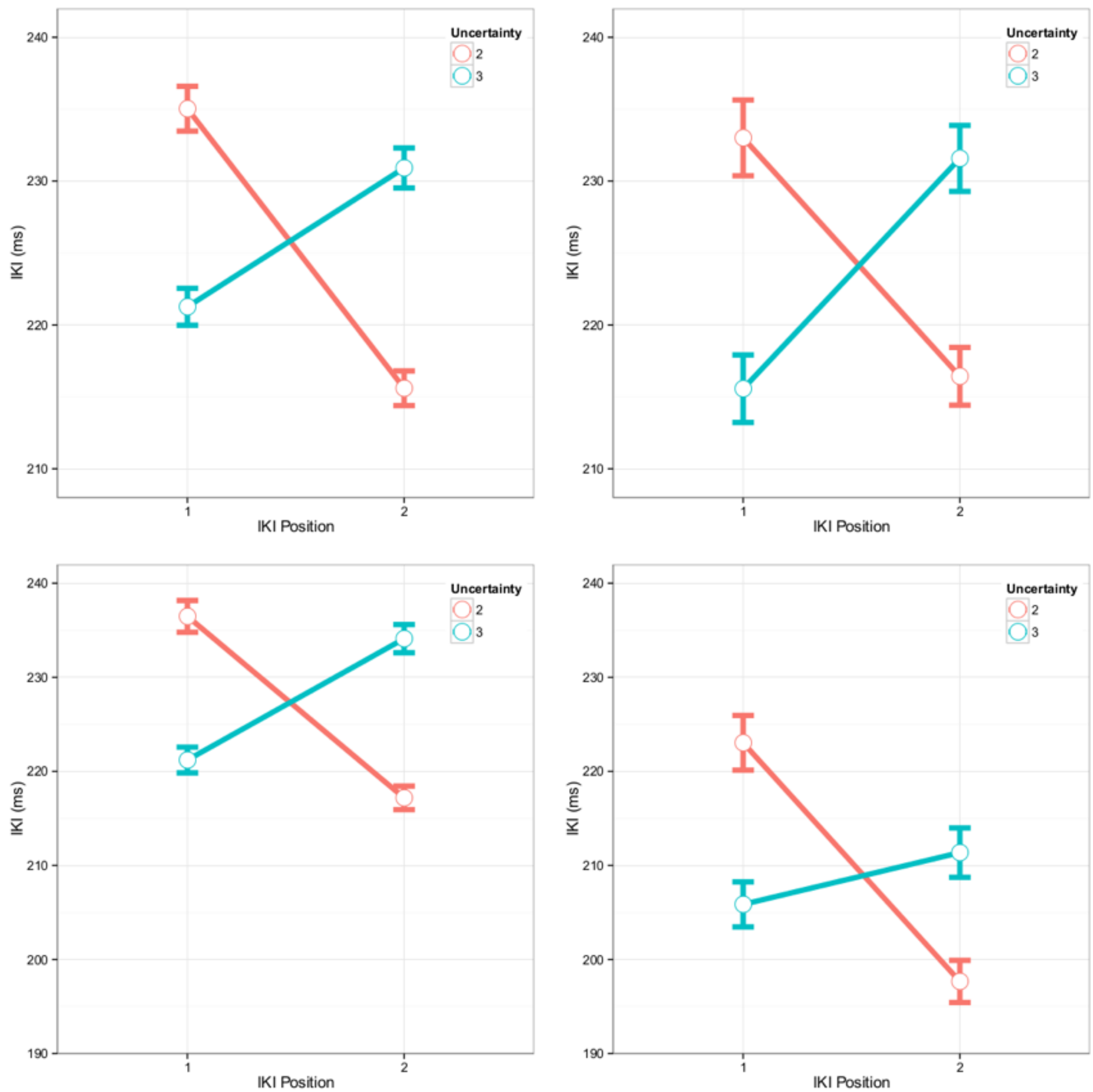
Supplementary material



Supplementary Figure 1. Mean IKI as a function of Uncertainty (on 2nd or 3rd element of the sequence) and Position within the sequence (first or second) for different subsets of the data. From top to bottom and left to right: Windows operating system, OS X operating system, Firefox web browser, Chrome web browser.