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ABC Versus QWERTZ: Interference From Mismatching Sequences of Letters in the Alphabet and on the Keyboard

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Letters have a position in the alphabet and they have a position on standard personal computer keyboards. The present study explored the consequences of compatibility between spatial codes representing letter position in the alphabet and on the keyboard. In Experiment 1, participants responded faster to letter dyads in an alphabetic order judgment task, when the letters' alphabetical order matched their left to right order on the keyboard. In Experiment 2, compatible dyads were typed more quickly than incompatible dyads. Finally, in Experiments 3 and 4, letter dyads with compatible alphabetical and keyboard sequences of letters were more preferred than dyads with incompatible orders. Together, these results suggest that the perception of letters concurrently activates 2 representations of ordinal sequences. Compatibility between these representations enhances performance as well as affective evaluations. Limitations of this alphabet–keyboard compatibility effect as well as implications for the development of formal typing courses and computer keyboard design are discussed.

Keywords: spatial compatibility, motor processes, dimensional processing, perceptual motor coordination, embodiment

Across time, people have established different systems for organizing letters. In addition to the classical alphabetical arrangement, technical advances necessitated the design of other forms of letter arrangements, which enable us to type efficiently using technical devices. Next to the very place-saving form of letter arrangement on a mobile phone (up to four letters share one key) standard keyboards have been created to operate personal computers. The organization of letters on computer keyboards has been adopted from classical typewriting machines, which had been arranged to prevent jamming of the keys. However, with modern computers, this is no longer necessary. Engineering designers have therefore advocated the use of keyboards with an alphabetic layout of letters (Norman & Fisher, 1982). So far, however, evidence for facilitating effects of alphabetic keyboards over standard keyboards is mixed (Michaels, 1971; Norman & Fisher, 1982). This was one point of departure for the present research. Among the questions that we asked was whether the left-to-right order of spatial letters in the alphabet could interfere with the use of keys on a standard keyboard if the spatial layout of the keys is from right to left and therefore conflicts with the alphabetic order.

Former research has demonstrated that letters are spatially represented because of their arrangement within the alphabet (Gevers, Reynvoet, & Fias, 2003). In the Gevers et al. (2003) study, participants performed an order-relevant task (target letter before or after *O*?) as well as an order-irrelevant task (consonant–vowel classification) with respect to the alphabetical letter arrangement. The authors found a strong response side effect for both tasks, meaning that subjects responded faster to letters before *O* with their left hand compared with keystrokes with their right hand and vice versa for letters after *O*. Moreover, Jou and Aldridge (1999) observed that pairwise comparisons of alphabetical order led to distance effects analogous to number comparisons (Moyer & Landauer, 1967). The authors let their participants decide whether a pair of letters was presented in the conventional (e.g., alphabetical) or unconventional order. The pattern suggests that response times decrease as the alphabetical distance between letters increases. These results indicate that letters are mentally represented on a horizontal line from left to right analogical to the alphabet. As a result, letters on the left side are associated with the left hand, whereas letters on the right side are associated with the right hand.

However, in typewriting, there is an alternative order of spatially representing letters, namely, according to the spatial position of letters on a standard QWERTZ computer keyboard.[1] There is considerable evidence that letters automatically activate corresponding keystrokes in skilled typists (Beilock & Holt, 2007; Jasmin & Casasanto, 2012; Logan, 2003; Rieger, 2004; Van den

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[1] According to Norman and Fisher (1982), in 1873, the Sholes brothers invented the QWERTY letter sequence for typewriting machines to minimize jamming of the keys when writing in the English language. This letter configuration has been adapted to the German language, resulting in the QWERTZ sequence. The only difference between these two configurations is that the *Y* and the *Z* keys were interchanged.

Bergh, Vrana, & Eelen, 1990; Yang, Gallo, & Beilock, 2009). As Van den Bergh et al. (1990) demonstrated, motor programs for finger movements are automatically activated when perceiving letters. In addition, Beilock and Holt (2007) showed that skilled typists prefer dyads typed with different fingers over those typed with the same finger using standard typing methods because of less motoric interference even when nothing was said about typing. Rieger (2004) further argued that this is not an unspecific activation of the finger, but rather an activation that includes the characteristics of the movements that are usually performed to type these letters. Moreover, Logan (2003) observed a Simon effect, reflecting faster responses when stimulus and the response assigned to that stimulus occur in the same part of space (for overviews, see Lu & Proctor, 1995; Simon, 1990), even in experiments in which subjects were instructed to type target letters on a computer keyboard. Letters on the left side of the computer keyboard can be typed faster when presented on the left side of the screen and vice versa for letters on the right side. These studies suggest that processing letters automatically activates spatial codes that represent the letters' location on computer keyboards. Letters on the left side of the computer keyboard are associated with the left hand, whereas letters on the right side are associated with the right hand.

In the present study, we asked whether spatial conflicts arise from these two possible ways of representing letters in typewriting. In fact, the sequential arrangement of letters within the alphabet is sometimes at odds with the sequence on the computer keyboard (see Figure 1). Gevers et al. (2003) showed that the mental representation of letters can be explained in a spatially horizontal manner from left to right. Taking into account that the arrangement of letters on the computer keyboard could be mentally represented in a spatial way as well (Rieger, 2004), one can imagine that compatibility between these two mental representations may be relevant. For example, in the dyad *W I* (see Figure 1), it becomes obvious that the letter *W* can be found on the left side of the keyboard, whereas the *I* is located on the right side. In contrast to the localization on the keyboard, the *I* can be found at the beginning section of the alphabet, whereas the *W* is at the end of the alphabet. As a consequence, such letter dyads might affect performance because of mismatching ordinal sequences within the alphabet and on the keyboard. Furthermore, studies concerning motor interference have shown that subjects preferred less interfering to highly interfering stimuli (Beilock & Holt, 2007; Van den Bergh et al., 1990). Moreover, subjects seem to prefer stimuli that are processed more efficiently or rather more fluently (Bornstein & D'Agostino, 1992, 1994; Topolinski & Strack, 2009; Whittlesea, 1993) or those that they can act on more fluently (Beilock & Holt, 2007; Hayes, Paul, Beuger, & Tipper, 2008), even if they do not have to conduct the associated motoric response. If alphabet–keyboard compatibility affects performance, on the basis of these studies, one would assume that even preference judgments should be influenced by alphabet–keyboard compatibility. Accordingly, we conducted four experiments to clarify whether alphabet–keyboard compatibility affects performance (Experiments 1 and 2) as well as evaluative judgment (Experiments 3 and 4).

There are at least two possible explanations for the proposed type of incongruence. First, this incongruence can be explained in terms of overlap between the two spatial dimensions (*S-S-overlap account*). According to the dimensional overlap model, the proposed type of incongruence could be described as S-S incongruence (Kornblum, 1992; Kornblum, Hasbroucq, & Osman, 1990; Kornblum & Lee, 1995). This model distinguishes different kinds of overlap that may occur between (a) relevant stimulus and response dimensions (*relevant S-R overlap*), (b) irrelevant stimulus and response dimensions (*irrelevant S-R overlap*), or (c) two stimulus dimensions (*S-S overlap*). As particular instances of overlapping dimensions are either matched or mismatched, the literature on spatial compatibility (e.g., Hommel, 1997; Kornblum, 1994; Kornblum & Lee, 1995) has distinguished between S-S and S-R compatibility. Letters as stimuli differ, on the one hand, with regard to their arrangement within the alphabet and, on the other hand, with regard to their position on the computer keyboard. Because letters (a) seem to activate a spatial representation reflecting the alphabet in a horizontal manner, leading to specific response side activations with respect to their location in the alphabet (Gevers et al., 2003), and (b) may also promote response side activations given their location on the computer keyboard (Beilock & Holt, 2007; Logan, 2003; Rieger, 2004), it could be reasoned that these two spatial codes can either match or mismatch. Given that studies concerning S-S compatibility typically show that responses to S-S-compatible trials are faster compared with responses to S-S-incompatible trials (Kornblum, 1994; Zhang,

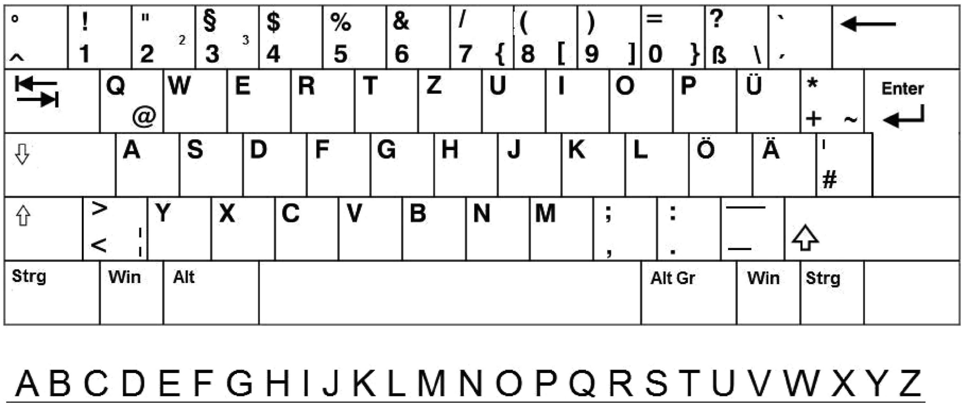

Figure 1. Illustration of letter arrangement on a QWERTZ keyboard and within the alphabet.

1996), one would expect that performance in response to S-S-compatible letter dyads, which we characterize as those with matching spatial codes, would be enhanced compared with S-S-incompatible dyads. Similarly, as less interfering stimuli are preferred over highly interfering ones (Beilock & Holt, 2007; Van den Bergh et al., 1990), subjects should prefer S-S-compatible dyads over incompatible ones.

Alternatively, it is conceivable that the alphabet–keyboard compatibility effect is modulated by the general scanning habit of the subjects (*dimensional processing account*).[2] Given the common reading direction, observers dominantly perceive from left to right, causing the region around a fixation point from which visual information is acquired to be asymmetric to the right (McConkie & Rayner, 1976). Subjects primarily use visual information to the right of the center of vision. Pollatsek, Bolozky, Well, and Rayner (1981) further demonstrated that the perceptual span is asymmetric to the right only when reading English (from left to right), but asymmetric to the left when reading Hebrew (from right to left). Thus, the asymmetry is due to the common reading direction rather than hemispheric specialization. Consequently, the scanning habits seem to be mapped onto the common reading direction. According to the literature on spatial compatibility effects, there is substantial evidence indicating that a spatial stimulus code is formed because attention is moved to the location of that stimulus (Rubichi, Nicoletti, Iani, & Umiltà, 1997; Stoffer, 1991; Stoffer & Umiltà, 1997; Umiltà & Nicoletti, 1992). As letters need to be read and therefore are processed from left to right, too, the general scanning habit that produces an attention shift during reading might contribute to the proposed type of compatibility effect. If this process is a relevant feature of the alphabet–keyboard compatibility effect, then one would expect that this effect would be restricted to the condition in which the sequence of letters maps onto the common reading direction.

Experiment 1

In Experiment 1, we tested the hypothesis that letters coactivate mental representations of the typical ordinal sequences of letters within the alphabet and on the computer keyboard by having participants perform an order-relevant task with respect to the alphabetical letter arrangement. According to the literature (Hamilton & Sanford, 1978; Jou & Aldridge, 1999; Lovelace & Snodgrass, 1971), in this so-called *alphabetic order judgment task*, participants are instructed to decide whether the left-to-right order of two horizontally presented letters matches the sequential order of these letters in the alphabet. According to the embodiment literature, stimuli are represented by covertly simulating the motoric response that is typically associated with that specific type of stimuli (Barsalou, 1999; Semin & Smith, 2008). As typing is considered the associated motoric response that is activated automatically when perceiving letters (Beilock & Holt, 2007; Jasmin & Casasanto, 2012; Rieger, 2004; Van den Bergh et al., 1990; Yang et al., 2009), the spatial code reflecting the letter sequence on the computer keyboard should influence the performance in an alphabetic order judgment task. As a consequence, we expected responses to S-S-compatible letter dyads to be faster compared with responses to S-S-incompatible dyads. If the alphabet–keyboard compatibility effect is restricted to the conditions in which the sequence of letters maps onto the common reading direction, then the dimensional processing account would be the appropriate explanation. But if the effect is independent of the common reading direction, then the appropriate explanation would be due to the S-S-overlap account.

Furthermore, we manipulated the frequency with which dyads usually appear in the German language to control for possible frequency effects. When performing an alphabetic order judgment, participants are forced to represent the alphabetical letter sequence to fulfill this task. They are instructed to classify the stimuli presented with respect to the conventional alphabetic order. Thus, one might speculate that a feeling of familiarity might be an important cue for fulfilling this task. Literature on the topic of processing fluency has repeatedly shown that an illusion of familiarity due to ease of retrieval leads to more false alarms on recognition tasks (see Whittlesea, 1993, for an overview). According to these studies, subjects even render their recognition judgments based on familiarity. One might assume that participants also render an alphabetic order judgment based on familiarity, as dyads reflecting a correct order with respect to the alphabet might be more familiar than dyads reflecting an incorrect order. If familiarity is used as a cue for fulfilling an alphabetic order judgment task, any additional source of familiarity should conflict with the actual task. As a consequence, dyad frequency should influence response latencies because it is well known that frequency of exposure and the feeling of familiarity are positively correlated (Bornstein, 1989; Bornstein & D'Agostino, 1992; Zajonc, 1968, 1980). We assumed that responses to rare dyads would be faster than responses to frequent dyads as higher frequency leads to a conflicting feeling of familiarity. Moreover, one might assume that these different kinds of interference—interference due to incompatibility between ordinal sequences of letters versus interference due to frequency-induced familiarity—accumulate, resulting in the slowest responses to frequently used, S-S-incompatible dyads.

Method

Participants. Forty-seven (34 women, 13 men) German undergraduate psychology students from the University of Trier participated for course credit. All had normal or corrected-to-normal visual acuity, and their native language was German.

Literature on the topic of automatic activation of corresponding keystrokes has shown that this activation process occurs in skilled typists only (Beilock & Holt, 2007; Rieger, 2004, 2007; Van den Bergh et al., 1990). Beilock and Holt (2007) relied on four criteria to classify subjects as skilled typists: (a) Participants must have taken a formal typing course, (b) they must type a minimum of 3 hr/week, (c) they must report that they keep their fingers on the "home keys," and (d) they must report that they only occasionally look at the keyboard. As one might argue that a representation of the letter arrangement according to the computer keyboard might be activated in skilled typists exclusively, we collected data according to these four criteria in our experiment to control for possible expertise effects. Because only two of the 47 participants met all of the criteria, we divided our sample in subjects who met at least three criteria versus those who did not. As analysis of the results yielded no influence of typing expertise on our data, we disregarded this aspect in the current study.

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[2] We thank an anonymous reviewer for offering this explanation.

Table 1
Stimulus Dyads and Their Attributes

Letter dyad	Alphabet	Keyboard	Compatibility	Dyad frequency	
A N	L → R	L → R	Matching	102	Frequent
F U	L → R	L → R	Matching	24	Frequent
C K	L → R	L → R	Matching	14	Frequent
D I	L → R	L → R	Matching	93	Frequent
W I	R → L	L → R	Mismatching	36	Frequent
R O	R → L	L → R	Mismatching	30	Frequent
S P	R → L	L → R	Mismatching	22	Frequent
S K	R → L	L → R	Mismatching	11	Frequent
O R	L → R	R → L	Mismatching	50	Frequent
K R	L → R	R → L	Mismatching	13	Frequent
N W	L → R	R → L	Mismatching	29	Frequent
L S	L → R	R → L	Mismatching	22	Frequent
U C	R → L	R → L	Matching	16	Frequent
I E	R → L	R → L	Matching	163	Frequent
P A	R → L	R → L	Matching	16	Frequent
L D	R → L	R → L	Matching	14	Frequent
A O	L → R	L → R	Matching	0	Rare
C P	L → R	L → R	Matching	0	Rare
F J	L → R	L → R	Matching	0	Rare
C N	L → R	L → R	Matching	0	Rare
W P	R → L	L → R	Mismatching	0	Rare
Q I	R → L	L → R	Mismatching	0	Rare
Y N	R → L	L → R	Mismatching	0	Rare
X J	R → L	L → R	Mismatching	0	Rare
P W	L → R	R → L	Mismatching	0	Rare
M X	L → R	R → L	Mismatching	0	Rare
P Q	L → R	R → L	Mismatching	0	Rare
J W	L → R	R → L	Mismatching	0	Rare
U Q	R → L	R → L	Matching	0	Rare
K C	R → L	R → L	Matching	0	Rare
J D	R → L	R → L	Matching	0	Rare
J C	R → L	R → L	Matching	0	Rare

Note. Classification of dyads as matching versus mismatching based on spatial compatibility and as rare versus frequent based on dyad frequency in the German language. Compatibility arises from overlap between orientations within the alphabet versus on the computer keyboard. L → R = orientation from left to right; R → L = orientation from right to left.

Materials. We constructed 32 letter dyads in terms of their spatial orientation within the alphabet and on the computer keyboard (see Table 1). Half of the dyads were oriented from left to right within the alphabet, which means that the sequential arrangement was correct. The other half was oriented from right to left, representing an incorrect sequential arrangement with regard to the alphabet.

Because of the fact that the global configuration of letters on the computer keyboard is also arranged horizontally, one can additionally specify the orientation of the two letters in a dyad on the keyboard. Here again, half of the dyads were oriented from left to right, which meant that the first letter was located on the left side of the keyboard, whereas the second one was located on the right side. The orientation of the other half of the dyads was vice versa. In a comparative judgment task, such as the one used in this experiment, participants are required to determine which of the two items comes first in a common sequence. Even though it does not matter how many irrelevant items are positioned between the two target items, this task-irrelevant stimulus attribute is activated parenthetically (Jou & Aldridge, 1999; Lovelace & Snodgrass, 1971; Moyer & Landauer, 1967). Because it is well known that response times decrease as the alphabetical distance between letters increases (Jou & Aldridge, 1999; Lovelace & Snodgrass, 1971), it cannot be ruled out that the representation of the common letter sequence on the keyboard causes similar effects, as the letter arrangement on the keyboard could be mentally represented in a spatial way as well (Rieger, 2004). Letter dyads differ on the one hand according to the hands involved in typing: Following the terminology of Gentner, Grudin, Larochelle, Norman, and Rumelhart (1983), one can distinguish between 1H dyads (sequences typed by one hand) and 2H dyads (sequences typed by two hands). On the other hand, one can specify the distance between the two letters on a keyboard. As these two factors might be confounded, we decided to use 2H dyads in our experiment exclusively.

Thus, the different spatial arrangements of the alphabet (left-to-right vs. right-to-left) and the keyboard (left-to-right vs. right-to-left) can be matched, which means that compatibility is given (e.g., *C K*), or can be mismatched, meaning that compatibility is not given (e.g., *L S*).

In addition to varying compatibility between letter sequences within the alphabet and on the keyboard, we manipulated the frequency with which dyads usually appear in the German language to control for possible frequency effects. Classification data from Bauer (2000) were used to estimate linguistic usage in the German language. Bauer analyzed text material printed in the German newspaper *Süddeutsche Zeitung* in March 1992. Therefore, linguistic usage is specified as "rare" if there is no occurrence within the analyzed text material. Dyads are called "frequent" if there are more than 10 occurrences. To control for possible distance effects (Jou & Aldridge, 1999; Lovelace & Snodgrass, 1971), we matched dyads with respect to the distance between letters within the alphabet.

Procedure. This experiment was conducted on a personal computer using a standard QWERTZ keyboard as input device. Letter dyads were presented in a random order on the screen. Each of the 32 dyads was presented twice, resulting in 64 experimental trials. In each trial, participants had to decide as quickly as possible whether the two letters presented were in the correct order concerning the alphabet using two marked keys (*X* vs. *N*) on the computer keyboard. Half of the participants were instructed to press the left key when the sequential order of letters was correct, and the right key was to be used to classify incorrect sequences. The other half of the participants were instructed to use these two keys in the opposite order, namely, the right key to indicate a correct order and the left key for an incorrect order.

At the end of the experiment, participants were asked what they thought could be the construction criteria of the letter dyads. Nobody indicated assuming any relation between alphabet and computer keyboard.

Results

Response latencies in the alphabetic order judgment task were analyzed. Outlier trials below 250 ms and above 2,500 ms (6.83% of the trials), as well as errors (an additional 9.07% of the trials) were excluded. A 2 (compatibility: ordinal letter sequences matched vs. mismatched) × 2 (dyad frequency: rare vs. frequent) × 2 (key allocation: left key = correct order/right key = incorrect order vs. vice versa) analysis of variance (ANOVA) was conducted on the remaining response latencies. This analysis yielded a significant main effect of frequency, $F(1, 45) = 24.06$, $p < .001$, $\eta_p^2 = .35$, with faster responses to rare dyads ($M = 1{,}126$ ms, $SE = 28$) compared with frequent dyads ($M = 1{,}200$ ms, $SE = 30$). Furthermore, we found a significant main effect of compatibility, $F(1, 45) = 49.44$, $p < .001$, $\eta_p^2 = .52$, reflecting faster responses to matching dyads ($M = 1{,}100$ ms, $SE = 29$) compared with mismatching dyads ($M = 1{,}227$ ms, $SE = 30$). To decide whether reading biases contributed to the compatibility effect, we separated this factor into two independent factors: (a) orientation within the alphabet (left-to-right vs. right-to-left) and (b) orientation on the keyboard (left-to-right vs. right-to-left). This analysis yielded a main effect of orientation within the alphabet, $F(1, 45) = 32.07$, $p < .001$, $\eta_p^2 = .42$, with faster responses to left-to-right dyads ($M = 1{,}118$ ms, $SE = 29$) compared with right-to-left dyads ($M = 1{,}218$ ms, $SE = 30$), as well as a main effect of orientation on the keyboard, $F(1, 45) = 81.14$, $p < .001$, $\eta_p^2 = .64$, with faster responses to left-to-right dyads ($M = 1{,}105$ ms, $SE = 28$) compared with right-to-left dyads ($M = 1{,}231$ ms, $SE = 30$). The interaction between these two factors was significant as well, $F(1, 45) = 40.23$, $p < .001$, $\eta_p^2 = .47$, indicating the compatibility effect. However, orthogonal Helmert contrasts revealed that the compatibility effect was restricted to the left-to-right condition: Responses to matching dyads with a left-to-right orientation within the alphabet and on the keyboard ($M = 999$ ms, $SE = 32$) significantly differed from responses to the two mismatching conditions ($M = 1{,}227$ ms, $SE = 30$), $F(1, 45) = 108.00$, $p < .001$, $\eta_p^2 = .70$, whereas responses to matching dyads with a right-to-left orientation within the alphabet and on the keyboard ($M = 1{,}226$ ms, $SE = 34$) did not differ from responses to the two mismatching conditions ($F < 1$, *ns*).

Moreover, as illustrated in Table 2, we found a significant interaction between frequency and compatibility, $F(1, 45) = 14.04$, $p < .01$, $\eta_p^2 = .24$. Frequent dyads revealed a strong compatibility effect, $t(46) = -7.20$, $p < .001$, $d = 1.47$, whereas this effect was much weaker for rare dyads, $t(46) = -3.48$, $p < .01$, $d = 0.69$. Manipulation of key allocation yielded only a significant main effect, $F(1, 45) = 9.52$, $p < .01$, $\eta_p^2 = .17$, with faster responses to left key = correct/right key = incorrect allocation ($M = 1{,}078$ ms, $SE = 40$) compared with the reverse allocation ($M = 1{,}249$ ms, $SE = 39$).

Discussion

This experiment was designed to investigate whether letters coactivate the mental representation of the letter arrangements within the alphabet and on the computer keyboard. Although participants showed no awareness of the construction criteria of letter dyads, we found a strong alphabet–keyboard compatibility effect, which, however, was restricted to the left-to-right condition. Using a comparative judgment task with respect to the alphabet, namely an alphabetic order judgment, we found a main effect of orientation within the alphabet (faster responses to left-to-right dyads compared with right-to-left dyads), replicating the pattern reported by Lovelace and Snodgrass (1971). This effect is typically explained by assuming that the alphabet is a serial list that is essentially unidirectional, so that subjects "are *looking for* forward pairs in that they are making a yes-no judgment about correct alphabetic order" (Lovelace & Snodgrass, p. 263). An alternative explanation could be the above-mentioned scanning habit during reading, so that responses to letter dyads that are mapped onto this direction (those with a left-to-right orientation within the alphabet) were faster compared with responses to dyads with a right-to-left orientation.

However, response latencies are affected by the irrelevant stimulus dimension, namely the sequence of letters on the computer keyboard, too: Responses to letter dyads with a left-to-right orientation on the keyboard were faster compared with responses to dyads with a right-to-left orientation. As typing is considered the associated motoric response that is activated automatically when

Table 2
Mean Reaction Times (ms) and Standard Errors for Matching and Mismatching Dyads and for Rare and Frequently Used Dyads, Experiment 1

	Dyad frequency			
	Rare		Frequent	
Variable	*M*	*SE*	*M*	*SE*
Matching dyads	1,091	30	1,110	31
Mismatching dyads	1,162	30	1,291	34
Compatibility effect	71		181	

Note. Compatibility effect is presented, reflecting mean reaction times for mismatching minus matching dyads.

perceiving letters (Beilock & Holt, 2007; Jasmin & Casasanto, 2012; Rieger, 2004; Van den Bergh et al., 1990; Yang et al., 2009) and *left* and *right* seem to be part of the keypress schemata (Logan, 2003), our data suggest that left hand/right hand responses were faster than right hand/left hand responses, which could be explained in terms of a correspondence effect between processing direction during reading and action direction during typing. Actually, Wing, Church, and Gentner (1989) observed that participants who are asked to synchronize between-hands or within-hand keystrokes to a tone to maintain a given tapping frequency tend to speed up left-to-right sequences but tend to slow down right-to-left sequences (Wing et al., Figure 2). Although this task is not directly comparable to typing, the results further substantiate the assumption that performance is enhanced when action direction maps onto the processing direction. The interaction further indicates that the fastest responses can be observed when the spatial code with respect to the orientation within the alphabet maps onto the orientation of the associated response keys during typing. However, this is restricted to the left-to-right condition, which corresponds to the common reading direction in our participants. This pattern is in line with the finding that the Simon effect depends on correspondence between the direction of the attention shift and action direction (Rubichi et al., 1997; Stoffer, 1991; Stoffer & Umiltà, 1997; Umiltà & Nicoletti, 1992), even though the Simon effect is not restricted to the condition in which attention is directed from left to right. However, the Simon effect is based on actually presenting stimuli in different locations of the computer screen with reference to a fixation point. In our experiment using letter dyads with different ordinal letter sequences with respect to the alphabet and the keyboard, the stimulus remained at the center of the screen, whereas attention was automatically directed from left to right appropriate to the common reading direction. Therefore, it is explicable that the alphabet–keyboard compatibility effect in our study was restricted to the left-to-right condition.

Furthermore, subjects needed more time to perform the sequential order task with frequent than with rare dyads. Moreover, the crucial alphabet–keyboard compatibility effect was more pronounced with frequent dyads than with rare dyads. As explained in the introduction, we assumed that a feeling of familiarity might have interfered with the actual task, as frequent dyads might be more familiar than rare dyads. One mechanism considered to underlie the performance in a comparison task (e.g., alphabetic order judgments) is a serial search process (Jou, 1997; Jou & Aldridge, 1999; Moyer, 1973; Moyer & Bayer, 1976; Parkman, 1971). Concerning the alphabetical letter sequence, a specific stimulus–response chain is learned in the first year of school (Jou, 1997; Jou & Aldridge, 1999), so that there are strong associations between adjacent letters. When fulfilling an alphabetic order judgment, this stimulus–response chain is considered to be reactivated by mentally running through the sequence (Jou, 1997; Jou & Aldridge, 1999). Thus, differences in frequency of occurrence might disturb this reactivation process because there are also strong associations between the two letters of a frequently used dyad. However, the interaction between compatibility and frequency can be explained in terms of parallel activation of consecutive keystrokes. According to the literature, typing seems to be the associated motoric response that is activated when dealing with letters (Beilock & Holt, 2007; Jasmin & Casasanto, 2012; Rieger, 2004; Van den Bergh et al., 1990; Yang et al., 2009). However, it remains open whether all letter dyads—independent of their attributes—lead to motoric response activations in the same manner. One might assume that only frequently used dyads are able to activate typing of consecutive keystrokes because the letter sequence in frequent dyads is practiced many times, whereas rare dyads may not promote parallel activation of motoric responses given unavailable practice. There are at least two lines of evidence suggesting that especially frequent dyads cause parallel activation of consecutive keystrokes. First, interkey intervals seem to be shorter when typing frequent dyads compared with rare dyads (Gentner, Larochelle, & Grudin, 1988; Salthouse, 1984; Terzuolo & Viviani, 1980). Although this pattern is typically explained in terms of practice effects, an alternative explanation would be the above-mentioned difference in parallel activation of consecutive keystrokes between frequent and rare dyads. Second, keystroke execution processes for each letter in the stimulus are activated in parallel only in response to words, but not in response to random letter strings (Crump & Logan, 2010; Larochelle, 1983; Shaffer & Hardwick, 1968; Sternberg, Knoll, & Wright, 1978). As we compared frequently used dyads with rare dyads that do not occur in standard text material (Bauer, 2000) in our study, it can be reasoned that frequent dyads are typically part of words, whereas rare dyads are not. Having a closer look at the Larochelle (1983) study, indeed, it becomes obvious that words (or pseudowords) and nonwords differed in terms of their mean digraph frequency. The nonwords used in this study had a much lower mean digraph frequency than the words (or pseudowords). As a consequence, we argue that especially frequent dyads cause parallel activation of consecutive keystrokes. From this point of view, it becomes explicable that in an alphabetic order judgment task, a conflicting representation with respect to the letter arrangement on the computer keyboard appears to be stronger in response to frequent dyads.

Experiment 2

In Experiment 1, participants were required to indicate whether letter dyads were in an alphabetical sequence or not. Thus, the alphabetical letter arrangement was task-relevant, and one might object that the activation of corresponding mental representations did not occur automatically. To replicate the alphabet–keyboard compatibility effect, in Experiment 2, we had participants perform an order-relevant task with respect to the sequence on a computer keyboard, namely a discontinuous typing task. This allowed us, on the one hand, to examine whether the alphabetical letter arrangement as the irrelevant stimulus dimension would be activated when the location of letters on the computer keyboard becomes the relevant stimulus dimension; on the other hand, it allowed us to clarify the consequences that might arise when using a computer keyboard as a medium for writing. Do mental representations of letters on the keyboard and within the alphabet and especially their compatibility have an impact on typing speed?

As the letter sequence on the keyboard can be characterized as the relevant stimulus dimension in a discontinuous typing task, we expected to replicate the alphabet–keyboard compatibility effect with letter position in the alphabet being the irrelevant stimulus dimension, which according to Gevers et al. (2003) is activated automatically when perceiving letters. As the results of Experiment 1 were in favor of the dimensional processing hypothesis, we again expected the alphabet–keyboard compatibility effect to be restricted to the left-to-right dyads.

We again manipulated frequency of appearance in the German language. As dyads were classified as rare when they had a frequency of zero according to the classification data from Bauer (2000), subjects were likely to have only little or no experiences in typing these dyads. Furthermore, it is well known that interkey interval and dyad frequency are negatively correlated (Gentner et al., 1988; Salthouse, 1984; Terzuolo & Viviani, 1980). Therefore, we expected subjects to type frequently used dyads much faster than rare dyads. Thus, the frequency effect was expected to be inverted compared with Experiment 1. As frequency in natural language is not a true experimental variable, frequent and rare dyads differ in terms of other variables, such as the potential to be typed in parallel. In an alphabetic order judgment task, differences in familiarity and the association between the two letters of a dyad might contribute to the frequency effect, so that rare dyads could be judged faster compared with frequent dyads. However, in a discontinuous typing task, people have to rely on motoric plans to type the letters (see Cooper, 1983, for an overview). The inner–outer loop theory (Crump & Logan, 2010; Logan & Crump, 2009; Shaffer, 1975) suggests a division of the system controlling typewriting into two hierarchical steps. First, the outer loop that receives input from the world (e.g., written or spoken language) is responsible for the transformation of text or thoughts into a series of words. Second, an inner loop further transforms each word into a series of keystrokes corresponding to each letter; thus, Crump and Logan (2010) conceive it as a process that "translates information from the outer loop into keystrokes one chunk at a time" (p. 1377). When words are processed, the inner loop receives the entire word as a single chunk from the outer loop, whereas in case of random letter strings, it receives each letter as a single chunk from the outer loop. As a consequence, random letter strings should be represented in the form of several chunks and passed one letter at a time to the inner loop. Taking into account that frequent letter dyads are typically part of words, whereas rare dyads do not lead to parallel activation of keystrokes, especially in response to the first, then one would expect typing speed to be faster in response to frequent dyads compared with rare dyads. Furthermore, one might presume that an influence of a conflicting representation with respect to the alphabetical letter sequence especially occurs in response to rare dyads because the motor programs that are activated in parallel in response to frequent dyads should be used to fulfill a discontinuous typing task. Hence, in the case of rare dyads, the two keypresses should be activated one at a time, which might promote the influence of dimensional processing effects, whereas frequent dyads might lead to response activation of the two keypresses as one chunk.

Furthermore, we tested the influence of supplemental activation of the alphabet by using the term *alphabet* in the instruction. Bächtold, Baumüller, and Brugger (1998) showed that the SNARC effect (faster responses to small numbers with the left hand and to large numbers with the right hand; see Gevers & Lammertyn, 2005, for an overview) can be reversed simply by displaying a clock face while working on the practice trials because small numbers are located on the right side of the clock. According to Gevers et al. (2003), the alphabet is activated automatically when perceiving letters. When assuming that the compatibility effect depends on coactivation of mental representations of the alphabet and the computer keyboard, one might expect that supplemental activation of the alphabet would lead to an increase in the alphabet–keyboard compatibility effect in a task in which the letter arrangement on the computer keyboard is the relevant stimulus dimension.

Method

Participants. Sixty-three (37 women, 26 men) German undergraduate psychology students from the University of Trier participated for course credit. All had normal or corrected-to-normal visual acuity, and their native language was German. Participants were accepted only if they had not participated in Experiment 1.

Materials. The same 32 letter dyads that were constructed for Experiment 1 were used in this experiment.

Procedure. This experiment was introduced via different instructions to manipulate supplemental activation of the alphabet. We instructed half of the participants that "two letters from the alphabet will be presented respectively on the computer screen," whereas the other half were told that only "two letters will be presented respectively on the computer screen." Afterward, letter dyads were presented in a random order. Each dyad was presented in the center of the screen for 250 ms followed by a blank screen. Participants were further instructed to type the two letters they perceived as quickly as possible in the presented order using a standard QWERTZ keyboard.

Results

Response latencies for correct responses were analyzed as the period of time that was required from disappearance of the letter dyad to typing the second letter. Subjects received each dyad for 250 ms until it disappeared. Analyzing response latencies after disappearance is advantageous because of exclusion of outlier trials below 250 ms. Trials in which participants needed longer than 2,000 ms to type the first letter were also excluded from the analyses. A total of 4.9% of trials were eliminated.

A 2 (compatibility: ordinal letter sequences matched vs. mismatched) × 2 (dyad frequency: rare vs. frequent) × 2 (supplemental activation of the alphabet: no vs. yes) ANOVA was conducted on the remaining response latencies. This analysis yielded a significant main effect of frequency, $F(1, 61) = 189.82$, $p < .001$, $\eta_p^2 = .76$, with faster responses to frequent dyads ($M = 914$ ms, $SE = 31$) compared with rare dyads ($M = 1{,}070$ ms, $SE = 33$). Here, again, we found a significant main effect of compatibility, $F(1, 61) = 7.67$, $p < .01$, $\eta_p^2 = .11$, reflecting faster responses to matching dyads ($M = 980$ ms, $SE = 33$) compared with mismatching dyads ($M = 1{,}004$ ms, $SE = 31$). A separate analysis of the compatibility effect again revealed a main effect of orientation within the alphabet, $F(1, 61) = 20.68$, $p < .001$, $\eta_p^2 = .25$, with faster responses to left-to-right dyads ($M = 973$ ms, $SE = 31$) compared with right-to-left dyads ($M = 1{,}021$ ms, $SE = 33$), as well as a main effect of orientation on the keyboard, $F(1, 61) = 18.62$, $p < .001$, $\eta_p^2 = .23$, with faster responses to left-to-right dyads ($M = 968$ ms, $SE = 31$) compared with right-to-left dyads ($M = 1{,}026$ ms, $SE = 34$). The interaction between these two factors was significant as well, $F(1, 61) = 7.69$, $p < .01$, $\eta_p^2 = .11$, indicating the compatibility effect. Orthogonal Helmert contrasts again revealed that the compatibility effect was restricted to the left-to-right condition, as responses to matching dyads with a left-to-right orientation within the alphabet and on the keyboard ($M = 930$ ms, $SE = 31$) were faster compared with responses to the two mismatching conditions ($M = 1{,}004$ ms, $SE = 31$), $F(1, 61) = 49.81$, $p < .001$, $\eta_p^2 = .45$, whereas responses to matching dyads with a right-to-left orientation within the alphabet and on the keyboard ($M = 1{,}037$ ms, $SE = 36$) did not differ from responses to the two mismatching conditions, $F(1, 61) = 2.36$, $p = .27$.

Moreover, we found a marginally significant interaction between frequency and compatibility, $F(1, 61) = 3.77$, $p = .06$, $\eta_p^2 = .06$. Rare dyads revealed a compatibility effect ($M_{\text{match}} = 1{,}048$ ms, $SE_{\text{match}} = 35$; $M_{\text{mismatch}} = 1{,}092$ ms, $SE_{\text{mismatch}} = 31$), $t(62) = -2.74$, $p < .01$, $d = 0.45$, whereas this effect did not reach significance for frequently used dyads ($M_{\text{match}} = 913$ ms, $SE_{\text{match}} = 31$; $M_{\text{mismatch}} = 917$ ms, $SE_{\text{mismatch}} = 32$), $t < 1$, *ns*.

Concerning supplemental activation of the alphabet, no main effect could be found ($F < 1$, *ns*). However, the analysis yielded a significant interaction between compatibility and supplemental activation of the alphabet, $F(1, 61) = 6.56$, $p < .02$, $\eta_p^2 = .10$. If the alphabet was activated supplementarily, an effect of compatibility was found ($M_{\text{match}} = 976$ ms, $SE_{\text{match}} = 46$; $M_{\text{mismatch}} = 1{,}022$ ms, $SE_{\text{mismatch}} = 43$), $t(31) = -3.08$, $p < .01$, $d = 0.73$. By contrast, if the alphabet was not activated supplementarily, the compatibility effect was not significant ($M_{\text{match}} = 985$ ms, $SE_{\text{match}} = 47$; $M_{\text{mismatch}} = 987$ ms, $SE_{\text{mismatch}} = 44$), $t(30) = -1.06$, $p = .30$. In addition, we found a significant three-way interaction between frequency, compatibility, and supplemental activation of alphabet, $F(1, 61) = 5.33$, $p < .03$, $\eta_p^2 = .08$, as illustrated in Table 3. If the alphabet was activated supplementarily, an effect of compatibility was found for rare dyads, $t(31) = -5.67$, $p < .001$, $d = 1.39$, but not for frequent dyads ($t < 1$, *ns*). By contrast, if the alphabet was not activated supplementarily, the compatibility effect for rare dyads disappeared as well ($t < 1$, *ns*).

Discussion

In Experiment 2, we focused on the effects of alphabet–keyboard compatibility on typing speed. We assumed that compatibility between spatial codes reflecting the arrangement within the alphabet and on the computer keyboard would speed up typing performance when the letter sequences map onto the processing direction from left to right during reading. Subjects were instructed to type letter dyads as quickly as possible, and again, we observed the effect of alphabet–keyboard compatibility: Participants typed letter dyads more quickly if the left-to-right sequence in the alphabet maps onto the left-to-right sequence on the computer keyboard.

Table 3
Mean Reaction Times (Standard Deviations; ms) for Matching and Mismatching Dyads and for Rare and Frequently Used Dyads, With Supplemental Activation of the Alphabet, Experiment 2

	Supplemental activation of alphabet			
	No		Yes	
Variable	Rare	Frequent	Rare	Frequent
Matching dyads	1,059 (52)	910 (44)	1,037 (51)	915 (43)
Mismatching dyads	1,057 (44)	915 (45)	1,126 (44)	918 (44)
Compatibility effect	−2	5	89	3

Note. Compatibility effect is presented, reflecting mean reaction times for mismatching minus matching dyads.

Furthermore, the data suggest that the alphabet–keyboard compatibility effect can be found when the alphabet is additionally activated by using the term *alphabet* in the instructions, but not when this is not the case. This could be interpreted as evidence against the argument of Gevers et al. (2003), who assumed that the alphabet is activated automatically when perceiving letters. If the alphabet–keyboard compatibility effect could be switched on and off by using the term *alphabet* in the instruction, it could be reasoned that it is not the alphabetical letter sequence that is activated automatically and independent of the task set.

Concerning dyad frequency, the pattern suggests that frequently used dyads were typed much faster than rare dyads, which is in line with the finding that interkey interval and dyad frequency are negatively correlated (Gentner et al., 1988; Salthouse, 1984; Terzuolo & Viviani, 1980). On the one hand, it is not surprising that those could be typed more quickly in our experiment, as frequent dyads are typed much more often in everyday life. On the other hand, this main effect further substantiates the assumption that frequent dyads cause parallel activation of consecutive keystrokes, whereas rare dyads do not. Moreover, as we expected, we found an interaction between frequency and compatibility that could be explained in terms of the assumed difference in parallel activation of consecutive keystrokes. We argue that frequent dyads cause parallel activation of consecutive keystrokes, whereas rare dyads cause gradual activation of keystrokes. The interaction suggests that the influence of alphabet–keyboard compatibility due to the processing direction from left to right during reading occurs in response to rare dyads only. This can be explained by the different processes of keypress activation. As frequent dyads might cause activation of corresponding keypresses in parallel, treating each dyad as one single chunk, participants lean on such motoric plans to type these dyads. Because of the fact that the keypresses are activated gradually in response to rare dyads treating each letter of the dyad as one chunk, attentional processes seem to affect typing performance especially in the latter case.

The influence of irrelevant letter positions on response times seemingly built up over time. In Experiment 2, the irrelevant dimension (alphabetic letter position) influenced response times during the slower responses only (with the low-frequency dyads). This seems to be in contrast to the pattern found in Experiment 1: Alphabet–keyboard compatibility especially influenced response times with high-frequency dyads. However, in Experiment 1, the influence of the irrelevant dimension (keyboard position) on response times was more pronounced during the slower responses (with the high-frequency dyads). The findings of Experiments 1 and 2 can thus be reconciled by assuming that the irrelevant dimension needed more time to take effect than the relevant dimension.

In summary, the data suggest that alphabet–keyboard compatibility has a positive impact on typing speed when the left-to-right orientation within the alphabet maps onto the left-to-right orientation on the keyboard, which is limited to responses to rare dyads when the alphabet is activated supplementarily via using the term *alphabet* in the instructions, as indicated by the three-way interaction. Therefore, we could repeatedly demonstrated an influence of alphabet–keyboard compatibility in an order-relevant task with respect to the letter arrangement on the computer keyboard.

Experiment 3

In Experiments 1 and 2, we examined the influence of alphabet–keyboard compatibility on performance. A compatibility effect could be demonstrated when either the alphabetical letter arrangement (Experiment 1) or the arrangement on the computer keyboard served as the relevant stimulus dimension (Experiment 2). However, it remains open whether this effect could be replicated in a task in which both stimulus dimensions could be characterized as irrelevant. Thus, in Experiment 3, we examined the influence of alphabet–keyboard compatibility on evaluative judgments because in this kind of task participants are not forced to activate one of the letter configurations.

According to the finding that subjects typically prefer less interfering over highly interfering stimuli (Beilock & Holt, 2007; Van den Bergh et al., 1990), we expected higher preferences for compatible dyads because of less spatial interference, which again should be restricted to the left-to-right condition. Here, again, we manipulated dyad frequency because it is well known that repeated exposure leads to more positive ratings as a consequence of increased familiarity (see Bornstein, 1989, for an overview). Indeed, Van den Bergh et al. (1990) reported that they found a general frequency-liking relationship for letter combinations. As a result, we expected higher preferences for frequently used dyads compared with rare dyads. Besides, in the literature there is consensus that subjects prefer stimuli that are processed more efficiently or rather more fluently (Bornstein & D'Agostino, 1992, 1994; Topolinski & Strack, 2009; Whittlesea, 1993). Similarly, subjects seem to prefer stimuli that they can act on more fluently (Beilock & Holt, 2007; Hayes et al., 2008), even if they do not have to conduct the associated motoric response. As typing seems to be the associated motoric response that is activated when perceiving letters (Beilock & Holt, 2007; Jasmin & Casasanto, 2012; Rieger, 2004; Van den Bergh et al., 1990; Yang et al., 2009), differences in typing speed should be reflected in evaluative judgments even when there is nothing said about typing. As a consequence, we expected to fully replicate the pattern found in Experiment 2: Alphabet–keyboard compatibility should take effect on preference when judging rare dyads but not when judging frequent dyads.

In Experiment 2, the pattern suggested that the alphabet–keyboard compatibility effect could be switched on and off by using the term *alphabet* in the instructions. This finding could be interpreted as evidence against Gevers et al. (2003), who argued that the alphabet is activated automatically when perceiving letters. However, one might argue that a discontinuous typing task is not appropriate to fully refute the assumption of Gevers et al., as the representation of the alphabetical letter arrangement, as an irrelevant stimulus dimension, might not appear because of the task requirements. Thus, in Experiment 3, we again examined the influence of supplemental activation of the alphabet by using the term *alphabet* in the instructions, as in an evaluative judgment task neither of the two stimulus dimensions could be characterized as relevant. If we could replicate the pattern found in Experiment 2, then this could be interpreted as further evidence against the Gevers et al. assumption; if not, the assumption that the alphabet is activated automatically should be limited to task sets in which no other competing letter arrangement is a relevant stimulus dimension.

Method

Participants. Thirty (18 women, 12 men) German undergraduate psychology students from the University of Trier participated for course credit. All had normal or corrected-to-normal visual acuity, and their native language was German. Participants were accepted only if they had not participated in one of the previous experiments.

Materials. The same 32 letter dyads that were constructed for Experiment 1 were used in this experiment.

Procedure. Again, this experiment was conducted on a computer with a standard QWERTZ keyboard as the input device. Letter dyads were randomly presented on the screen. In each trial, participants had to decide "whether they liked the dyad spontaneously or not using two marked keys on the computer keyboard." The left key (*X*) was to be pressed when they liked the dyad, whereas the right key (*N*) was to be used to indicate that they did not like the dyad. The response mapping was fixed so that each subject accomplished the task with the same key allocation. Although indicating liking with the left hand and disliking with the right hand can be considered as an incompatible mapping (cf. Casasanto, 2009), we decided to map the key allocation onto the task requirement, so that the sequence of options within the instructions (liking or not) coincided with the sequence of response keys.

To manipulate supplemental activation of the alphabet, we again instructed half of the participants that "two letters will be presented respectively on the computer screen," whereas the other half received the instructions that "two letters from the alphabet will be presented respectively on the computer screen." In addition, they were given instructions to judge spontaneously without paying attention to any associations to initials or abbreviations.

Results

A 2 (compatibility: ordinal letter sequences matched vs. mismatched) × 2 (dyad frequency: rare vs. frequent) × 2 (supplemental activation of the alphabet: no vs. yes) ANOVA was conducted for the preference judgments (see Table 4). This analysis yielded a significant main effect of frequency, $F(1, 28) = 30.15$, $p < .001$, $\eta_p^2 = .52$, with lower preference for rare dyads ($M = 0.44$, $SE = 0.03$) compared with frequent dyads ($M = 0.64$, $SE = 0.03$). Here, again, we found a significant main effect of compatibility, $F(1, 28) = 13.42$, $p < .01$, $\eta_p^2 = .32$, reflecting a greater preference for matching dyads ($M = 0.60$, $SE = 0.03$) compared with mismatching dyads ($M = 0.48$, $SE = 0.03$). However, in a separate analysis, orthogonal Helmert contrasts revealed that the compatibility effect was not restricted to the left-to-right condition: Preferences for matching dyads with a left-to-right orientation within the alphabet and on the keyboard ($M = 0.65$, $SE = 0.04$) were higher compared with preferences for the two mismatching conditions ($M = 0.48$, $SE = 0.03$), $F(1, 28) = 12.02$, $p < .01$, $\eta_p^2 = .29$, and that difference emerged for matching dyads with a right-to-left orientation within the alphabet and on the keyboard

Table 4
Mean Preferences (Standard Deviations) for Matching and Mismatching Dyads and for Rare and Frequently Used Dyads, With Supplemental Activation of the Alphabet, Experiment 3

Variable	Supplemental activation of alphabet			
	No		Yes	
	Rare	Frequent	Rare	Frequent
Matching dyads	0.45 (0.05)	0.66 (0.04)	0.60 (0.05)	0.68 (0.04)
Mismatching dyads	0.33 (0.05)	0.68 (0.05)	0.36 (0.05)	0.55 (0.05)
Compatibility effect	0.12	−0.02	0.24	0.13

Note. Compatibility effect is presented, reflecting preference for matching minus mismatching dyads. Data can range between 0.00 and 1.00. A score of 1.00 indicates that subjects liked all dyads of that category, whereas a score of 0.00 indicates that none of the dyads was liked.

($M = 0.56$, $SE = 0.02$), too, $F(1, 28) = 6.95$, $p < .05$, $\eta_p^2 = .19$. Neither the main effect of orientation within the alphabet, $F(1, 28) = 1.92$, $p = .22$, nor the main effect of orientation on the keyboard, $F(1, 28) = 1.01$, $p = .32$, reached significance.

Moreover, we found a significant interaction between frequency and compatibility, $F(1, 28) = 5.12$, $p < .05$, $\eta_p^2 = .16$. Rare dyads revealed a strong compatibility effect ($M_{\text{match}} = 0.52$, $SE_{\text{match}} = 0.04$; $M_{\text{mismatch}} = 0.35$, $SE_{\text{mismatch}} = 0.04$), $t(29) = 3.98$, $p < .001$, $d = 1.00$, whereas this effect did not reach significance for frequently used dyads ($M_{\text{match}} = 0.67$, $SE_{\text{match}} = 0.03$; $M_{\text{mismatch}} = 0.62$, $SE_{\text{mismatch}} = 0.03$), $t(29) = 1.59$, $p = .12$.

Concerning supplemental activation of the alphabet, no main effect could be found ($F < 1$, *ns*). However, the analysis yielded a significant interaction between compatibility and supplemental activation of the alphabet, $F(1, 28) = 4.52$, $p < .05$, $\eta_p^2 = .14$. If the alphabet was activated supplementarily, an effect of compatibility was found ($M_{\text{match}} = 0.64$, $SE_{\text{match}} = 0.03$; $M_{\text{mismatch}} = 0.46$, $SE_{\text{mismatch}} = 0.03$), $t(15) = 3.70$, $p < .01$, $d = 1.23$. By contrast, if the alphabet was not activated supplementarily, the compatibility effect did not reach significance ($M_{\text{match}} = 0.56$, $SE_{\text{match}} = 0.04$; $M_{\text{mismatch}} = 0.51$, $SE_{\text{mismatch}} = 0.04$), $t(13) = 1.33$, $p = .21$. In addition, we found a marginally significant interaction between frequency and supplemental activation of the alphabet, $F(1, 28) = 3.67$, $p = .07$, $\eta_p^2 = .12$. If the alphabet was not activated supplementarily, participants preferred frequent dyads ($M = 0.67$, $SE = 0.04$) over rare dyads ($M = 0.39$, $SE = 0.04$), $t(13) = -6.14$, $p < .001$, $d = 2.29$. By contrast, if the alphabet was activated supplementarily, this effect was somewhat smaller ($M_{\text{frequent}} = 0.62$, $SE_{\text{frequent}} = 0.04$; $M_{\text{rare}} = 0.48$, $SE_{\text{rare}} = 0.04$), $t(15) = -2.38$, $p < .05$, $d = 0.76$. The three-way interaction between compatibility, frequency, and supplemental activation of the alphabet did not reach significance ($F < 1$, *ns*).

Discussion

Experiment 3 was designed to investigate whether the alphabet–keyboard compatibility effect could be found for a task in which neither of the two stimulus dimensions could be characterized as relevant. Although participants were not forced to activate the sequential order of letters within the alphabet and on the keyboard when asked for preference judgments, indeed, we found a strong alphabet–keyboard compatibility effect. However, against our expectations, the alphabet–keyboard compatibility effect was not restricted to the left-to-right condition, but emerged in the right-to-left condition, too. According to the two alternative explanations presented in the introduction (S-S-overlap account vs. dimensional processing account), the results could be read in favor of the S-S-overlap account. Letters (a) seem to activate a response side with respect to their location within the alphabet (Gevers et al., 2003) and (b) lead to activations of the hand that would be used to type the letter (Beilock & Holt, 2007; Logan, 2003; Rieger, 2004). When both stimulus dimensions mismatched, preferences were diminished. Because the alphabet–keyboard compatibility effect was restricted to the left-to-right condition in Experiments 1 and 2, and there is a strong line of evidence showing that participants typically prefer stimuli that are processed more fluently (Bornstein & D'Agostino, 1992, 1994; Topolinski & Strack, 2009; Whittlesea, 1993) or that can be acted on more fluently (Beilock & Holt, 2007; Hayes et al., 2008), we expected the alphabet–keyboard compatibility effect to be restricted to the condition that corresponded to the common reading direction in an evaluative judgment task, too. This inconsistency might be explained in terms of the different task requirements: In an alphabetic order judgment task as well as a discontinuous typing task, it is necessary to process both letters individually; in the first case, both letters had to be compared and in the latter case both letters had to be typed. However, in an evaluative judgment task, this is not necessarily the case, because participants are required to judge the dyad as a whole. Consequently, the influence of dimensional processing might be intensified in an alphabetic order judgment task as well as a discontinuous typing task. This account could be further substantiated by the fact that we found neither a main effect of orientation within the alphabet nor a main effect of orientation on the keyboard, which could be explained in terms of differences in the direction of processing (see discussion of Experiment 1). However, having a closer look at the alphabet–keyboard compatibility effect, it becomes obvious that the effect size was somewhat smaller in the right-to-left condition compared with the left-to-right condition. Therefore, the dimensional processing explanation could not be fully ruled out.

Furthermore, the analysis yielded a main effect for frequency: Participants preferred frequent dyads over rare dyads, which is in accordance with the pattern reported by Van den Bergh et al. (1990) and could be explained in terms of the well-known general frequency-liking relationship as a consequence of increased familiarity (Bornstein, 1989). The interaction between frequency and compatibility reveals a similar pattern as in Experiment 2. Therefore, the conditions that are acted on less fluently are liked less (Beilock & Holt, 2007; Hayes et al., 2008), which indicates that typing as the associated motoric response seems to be activated and is used as a cue to render preference judgments so that differences in typing speed are reflected in evaluative judgments.

Concerning supplemental activation of the alphabet, we found a marginal significant interaction between frequency and supplemental activation, which we interpret in terms of the different cues that are used to render preference judgments. Typing as the associated motoric response might be activated, so that differences in the fluency with which this action would be accomplished might be reflected in evaluative judgments, especially when the alphabet is not activated supplementarily: Frequent dyads are preferred over rare dyads, as frequent dyads are typed more fluently, which could be explained in terms of parallel activation of consecutive keystrokes. However, if the alphabet is activated supplementarily, this effect is somewhat smaller, indicating that other cues (e.g., alphabetical information) are consulted as well to render preference judgments, diminishing the frequency effect.

Similar to Experiment 2, in which the alphabet–keyboard compatibility effect could be switched on by using the term *alphabet* in the task instructions, we found an interaction between supplemental activation and compatibility, indicating that the alphabet–keyboard compatibility effect especially occurs when the alphabet was named in the instructions. Therefore, it again could be queried whether the alphabet is activated automatically (Gevers et al., 2003). However, the lack of a three-way interaction between compatibility, frequency, and supplemental activation of the alphabet suggests that, unlike the pattern found in Experiment 2, the alphabet–keyboard compatibility effect is (a) not absent at all in the conditions in which the alphabet is not named in the instructions and (b) not absent at all when evaluating frequent dyads. Consequently, using the term *alphabet* in the instructions had an impact on the alphabet–keyboard compatibility effect in the predicted way, but the alphabet–keyboard compatibility effect could not be prevented at all by omitting supplemental activation of the alphabet. Thus, we conclude that the Gevers et al. (2003) assumption that the alphabet is activated automatically even when totally task irrelevant should be limited: In a task set in which a competing letter sequence serves as the relevant stimulus dimension (e.g., discontinuous typing task), the performance seems to be unaffected by the alphabetical letter sequence until this information is somehow activated. However, in an evaluative judgment task, the alphabetical letter sequence can have a slight influence on preferences even when the alphabetical letter sequence is not activated supplementarily.

Experiment 4

The results of Experiments 2 and 3 indicate that the alphabet–keyboard compatibility effect can be modulated by using the term *alphabet* in the task instructions. In a similar vein, it might be possible that activation of the letter sequence on the keyboard is influenced when accomplishing the task with a computer keyboard as response device. Actually, some studies have found empirical support for the assumption that typing-associated effects critically depend on performing the task on a computer keyboard. Using a serial response box as an external input device, the investigated typing-associated effects could not be demonstrated (Rieger, 2004). By contrast, other studies have suggested that the activation of corresponding keystrokes is automatic in nature (Beilock & Holt, 2007; Rieger, 2004, 2007). Taking this into account, one might argue that the contingency of having participants perform their task on a computer would suffice to activate the configuration on a keyboard. To find out whether the letter sequence on the computer keyboard would be automatically activated in our participants, we conducted Experiment 4 as a paper–pencil study to examine the influence of alphabet–keyboard compatibility on evaluative judgments. On the basis of the results found in Experiments 2 and 3, we additionally mentioned the alphabet in the instructions to make sure that the alphabet was actually activated. Given that we found an alphabet–keyboard compatibility effect in an evaluative judgment task that was accomplished at a computer (Experiment 3), the alphabet–keyboard compatibility effect should emerge in this experiment, too. However, it is unclear whether this pattern would favor the dimensional processing account (as it could be reasoned given the results of Experiments 1 and 2) or the S-S-overlap account (as suggested by the results of Experiment 3). Furthermore, we expected higher preferences for frequently used dyads compared with rare dyads due to a general frequency-liking relation (Bornstein, 1989; Bornstein & D'Agostino, 1992; Zajonc, 1968, 1980). As Experiment 3 demonstrated that alphabet–keyboard compatibility takes effect especially in response to rare dyads, we expected to replicate this interaction pattern.

Method

Participants. Sixteen (10 women, 6 men) German undergraduate psychology students from the University of Trier participated voluntarily. All had normal or corrected-to-normal visual acuity, and their native language was German.

Materials. The same 32 letter dyads that were constructed for Experiment 1 were used in this experiment.

Procedure. In this experiment, our 32 letter dyads were arranged on a questionnaire. Five different versions of randomly arranged questionnaires had been drawn up. Participants were instructed that "two letters from the alphabet are listed respectively" and their task was to decide whether they liked each dyad spontaneously or not by marking "yes" or "no" with a cross. Again, they were given the instructions to judge spontaneously without paying attention to any associations to initials or abbreviations.

Results

A 2 (compatibility: ordinal letter sequences matched vs. mismatched) × 2 (dyad frequency: rare vs. frequent) ANOVA was conducted for the preference judgments. This analysis yielded a significant main effect of frequency, $F(1, 15) = 7.15$, $p < .02$, $\eta_p^2 = .32$, indicating that frequent dyads ($M = 0.54$, $SE = 0.05$) were preferred more than rare dyads ($M = 0.40$, $SE = 0.04$). Again, we found a significant main effect of compatibility, $F(1, 15) = 5.42$, $p < .04$, $\eta_p^2 = .27$, reflecting a greater preference for matching dyads ($M = 0.51$, $SE = 0.04$) compared with mismatching dyads ($M = 0.43$, $SE = 0.04$). In a separate analysis, orthogonal Helmert contrasts again revealed that the compatibility effect was restricted to the left-to-right condition, as preferences for matching dyads with a left-to-right orientation within the alphabet and on the keyboard ($M = 0.58$, $SE = 0.06$) were higher compared with preferences for the two mismatching conditions ($M = 0.43$, $SE = 0.04$), $F(1, 15) = 6.69$, $p < .05$, $\eta_p^2 = .31$, whereas preferences for matching dyads with a right-to-left orientation within the alphabet and on the keyboard ($M = 0.49$, $SE = 0.03$) did not differ from preferences for the two mismatching conditions, $F(1, 15) = 1.10$, $p = .31$. Neither the main effect of orientation within the alphabet, $F(1, 15) = 1.12$, $p = .31$, nor the main effect of orientation on the keyboard, $F(1, 15) = 1.33$, $p = .27$, reached significance.

Moreover, as illustrated in Table 5, we found a marginally significant interaction between frequency and compatibility, $F(1, 15) = 3.12$, $p < .10$, $\eta_p^2 = .17$. Rare dyads revealed a strong compatibility effect, $t(15) = 4.14$, $p < .01$, $d = 1.42$, whereas this effect could not be found for frequently used dyads ($t < 1$, *ns*).

Discussion

The purpose of Experiment 4 was to clarify whether the alphabet–keyboard compatibility effect in an evaluative judgment task critically depends on accomplishing the task at a computer. Therefore, we conducted a paper–pencil study to remove physical contact to a computer keyboard. Here, again, we observed an alphabet–keyboard compatibility effect: Participants liked letter dyads with matching letter sequences within the alphabet and on the computer keyboard over mismatching ones. However, this effect seemed to be restricted to the left-to-right condition, which accords with the results of Experiments 1 and 2 (performance tasks), but seemed to be somewhat inconsistent with Experiment 3 (evaluative judgment). One possible explanation could be that the task requirement of reading information on a sheet of paper (containing letter dyads listed in two columns) enforced the tendency to read the information from left to right according to the common reading direction, whereas in Experiment 3, each dyad was presented individually on the screen, promoting the processing of the dyad as a whole instead of judging two individual letters.

Concerning dyad frequency, we again observed greater preferences for frequent over rare dyads, which is reasonable because of a general frequency-liking relationship (Bornstein, 1989). Again, the interaction pattern suggests that typing as the associated motoric response is activated, so that differences in typing speed are reflected in preference judgments: The dyads that participants could act on the fluently were liked the most (Beilock & Holt, 2007; Hayes et al., 2008).

In summary, we conclude that typing as the associated motoric response is not exclusively activated when interacting with a computer keyboard, as we again observed an alphabet–keyboard compatibility effect on preference judgments in this paper–pencil study.

Table 5
Mean Preferences (Standard Deviations) for Matching and Mismatching Dyads and for Rare and Frequently Used Dyads, Experiment 4

	Dyad frequency			
	Rare		Frequent	
Variable	*M*	*SD*	*M*	*SD*
Matching dyads	0.47	0.05	0.55	0.06
Mismatching dyads	0.33	0.04	0.54	0.06
Compatibility effect	0.14		0.01	

Note. Compatibility effect is presented, reflecting preference for matching minus mismatching dyads. Data can range between 0.00 and 1.00. A score of 1.00 indicates that subjects liked all dyads of that category, whereas a score of 0.00 indicates that none of the dyads was liked.

General Discussion

The experiments reported here demonstrate that the processing of letters automatically primes two types of position information, namely the position of a given letter in the alphabet and on the keyboard. Mutual compatibility between these codes affects letter processing over a broad range of behavioral measures. As demonstrated in Experiment 1, alphabet–keyboard compatibility influenced response latencies, with alphabetical letter sequence as the relevant stimulus dimension. In Experiment 2, typing speed was influenced by alphabet–keyboard compatibility, with letter sequence on a computer keyboard as the relevant stimulus dimension. Finally, letter dyads with compatible ordinal sequences were preferred over dyads with incompatible sequences (Experiments 3 and 4).

We introduced two possible explanations for this type of compatibility effect. First, this effect might be a result of response conflicts. As letters located on the left side of the alphabet seem to be associated with the left hand and letters on the right side seem to be associated with the right hand, response conflict might arise when the location of letters on the keyboard mismatch (S-S-overlap account). Second, general scanning habits due to the common reading direction seem to lead subjects to dominantly process visual information to the right of the center of fixation (McConkie & Rayner, 1976; Pollatsek et al., 1981). Therefore, the alphabet–keyboard compatibility effect might arise because of a match between processing direction and action direction (dimensional processing account). The crucial condition to decide between these alternatives seems to be the right-to-left condition. Whereas the S-S-overlap account predicts compatibility effects in either direction, the alphabet–keyboard compatibility effect should be confined to the left-to-right (reading) direction according to the dimensional processing account. The results of the present study are more easily reconciled with the dimensional processing account: In an alphabetic order judgment task (Experiment 1), a discontinuous typing task (Experiment 2), and an evaluative judgment task (Experiment 4), we observed an alphabet–keyboard compatibility effect that was restricted to the condition in which the construction of letter dyads mapped onto the common reading direction. Only in Experiment 3 (evaluative judgment task) did we find the alphabet–keyboard compatibility effect not to be restricted to the left-to-right condition, even though the dimensional processing explanation could not be ruled out at all. Therefore, we argue that the observed type of compatibility arises from the direction of processing from left to right during reading. Consequently, one would expect the alphabet–keyboard compatibility effect to be restricted to the right-to-left condition when examining, for example, participants whose native language is Hebrew (reading direction from right to left), which could be studied in the future to confirm the dimensional processing hypothesis. Moreover, because of the fact that we used letter dyads in our study, further research could deal with the question of whether such compatibility effects emerge in response to single letters, too.

However, it remains open whether hand position contributes to the alphabet–keyboard compatibility effect. We exclusively used 2H dyads in our study, which are letter sequences that would be typed with alternate hands. As the spatial compatibility effect even emerges under conditions in which responses are given with two fingers of the same hand (Heister, Ehrenstein, & Schroeder-Heister, 1986, 1987; Hommel, 1996), one would expect the alphabet–keyboard compatibility effect reported in this study not to be restricted to 2H dyads. But a necessary precondition that the alphabet–keyboard compatibility effect could be observed in response to 1H/2F dyads (one hand, two fingers), too, would be the activation of the specific finger that would be used to type the letter instead of a more general activation of the response hand. The data reported by Larochelle (1983) reveal that skilled typists' interkey intervals in responses to 1H/2F dyads are shorter compared with 1H/1F intervals, whereas novice typists do not show this effect. Therefore, one might assume that potential alphabet–keyboard compatibility effects in response to 1H dyads depend on typing skill. As in our sample nearly nobody met all of the four criteria to classify subjects as skilled typists (Beilock & Holt, 2007), future research is required to examine whether the alphabet–keyboard compatibility effect is restricted to the 2H conditions.

The current results are subject to some further limitations, especially with reference to the automaticity of the effect. Experiment 2 showed that the alphabet–keyboard compatibility effect was observed only when there was supplemental activation of the alphabet, and in Experiment 3, omission of using the term *alphabet* in the task instructions diminished the alphabet–keyboard compatibility effect. These results indicate that, unlike as Gevers et al. (2003) argued, the sequence of letters within the alphabet might not be activated automatically even when totally irrelevant to the task. Gevers et al. found a strong spatial response bias in an alphabetically order-relevant task (target letter before or after *O*) and in an order-irrelevant task (consonant–vowel classification). Because the order-relevant task forces participants to activate the arrangement of letters within the alphabet, it is not surprising that the authors found a response side effect. However, the order-irrelevant task cannot be explained by a forced activation of the spatial arrangement of the letters in the alphabet. Gevers et al. found a response side effect also when having participants perform a consonant–vowel classification, leading to the argument that the activation of the spatial representation of letters within the alphabet is an automatic process. But as Gevers et al. let their participants perform both tasks, one might imagine that for subjects who first performed the order-relevant task, the letter arrangement within the alphabet was still active when performing the order-irrelevant task.

Dehaene, Bossini, and Giraux (1993) also investigated whether a response side effect could be found for letters as stimuli by using two different tasks: consonant–vowel classification versus ACE–BDF classification. Compared with Gevers et al. (2003), Dehaene et al. let their participants perform only one of the two tasks. It is important to note that the latter did not observe a response side effect for the consonant–vowel classification. As simply using the term *alphabet* in the instructions sufficed to activate the sequential arrangement of letters within the alphabet, one might assume that the affordance of the experimental situation in the study reported by Gevers et al. might have determined that a response side effect could be observed. Therefore, further research should address the question of whether the mental representation of the alphabetic letter arrangement really is activated automatically or not.

However, the current findings do suggest that—in contrast to the alphabetical configuration—the activation of the letter arrangement on the computer keyboard seems to be an automatic process. As the alphabet–keyboard compatibility effect could not be eliminated by using paper–pencil questionnaires for rendering preference judgments (see Experiment 4), we conclude that the sequential arrangement of the computer keyboard is automatically activated when perceiving letters, a conclusion that is in line with findings reported in the literature (Beilock & Holt, 2007; Rieger, 2007; Van den Bergh et al., 1990; Yang et al., 2009). We explain this difference between the activation of the alphabetical sequence versus the sequence on the computer keyboard in terms of different degrees of daily routine. As typing is considered the associated motoric response to letters (Beilock & Holt, 2007; Jasmin & Casasanto, 2012; Rieger, 2004; Van den Bergh et al., 1990; Yang et al., 2009), it becomes explicable that the letter sequence on a computer keyboard seems to be the dominant one, and also because letters within the alphabet are typically not associated with a specific response. Nevertheless, we observed a stronger alphabet–keyboard compatibility effect when using the computer as a medium for rendering preference judgments compared with paper–pencil questionnaires. Such an influence on performance has been reported by Rieger (2004) as well. She observed that typing-related representations were more intensive when participants performed their task on a computer keyboard instead of an external device. Therefore, we understand the activation of spatial representation of the letter arrangement on the computer keyboard to be an automatic process. But further research is required to decide which letter arrangement has priority.

Another limitation results from the fact that our primary independent variables might be confounded with other relevant variables, such as familiarity or differences in activation of consecutive keystrokes that might be confounded with dyad frequency. To investigate the research question described in the introduction, it was essential to compare distinct letters sets. However, one major difficulty that arises from this circumstance is the possibility that other confounding variables potentially contribute to the effects reported in this study. Therefore, future research could attend to this issue by investigating the influence of potentially confounding variables.

Because of the extensive usage of computers in everyday life, it does not seem to be surprising that the arrangement on the keyboard is automatically associated with letters. However, one might question what consequences would arise when using different letter arrangements. Experiment 2 showed that even actual typing performance was negatively influenced by alphabet–keyboard compatibility, but only when there was supplemental activation of the alphabet. This result indicates that learning to type on the computer keyboard might be hindered because of the special arrangement of letters that is totally different from the familiar configuration within the alphabet, an assumption that has already been made by Norman and Fisher (1982): "An alphabetical arrangements [*sic*] would make sense to inexperienced typists, who today must spend considerable time learning the arbitrary arrangement of the Sholes keyboard" (p. 2). Thus, our results have important implications for the development of formal typing courses. We suggest that course instructors should refrain from activating the alphabet in any way, for example, by using the term *alphabet*.

The QWERTZ keyboard arrangement was invented to minimize the jamming of keys when typing on a classical typewriting machine (Norman & Fisher, 1982). As this is not a major concern with modern computers, over the years, much effort has been put toward developing alternative forms of computer keyboards (see Rohmert, 1982, for an overview). However, most of these ambitions were for ergonomic reasons: For example, Rohmert (1982) demonstrated a negative impact on typing speed as a consequence of unequal physical strain of different fingers. In addition, much effort has been made to establish alphabetic keyboard arrangements (Hirsch, 1970; Michaels, 1971; Norman & Fisher, 1982). As Hirsch (1970) and Michaels (1971) failed to show the superiority of alphabetic keyboards over the classical QWERTZ keyboard, Norman and Fisher (1982) decided to compare alphabetical arrangements with randomly ordered arrangements. They argue that even novice typists have some experience with computers, which is a circumstance that makes it necessary to use a randomly organized keyboard as a control. In this study, when examining novice typists, they found a significant effect of keyboard type reflecting superiority of alphabetical arrangements over randomly organized keyboards. Our study shows that the classical QWERTZ keyboard influences typing speed not only because of ergonomic considerations but also because of incompatibility between the QWERTZ sequence and the alphabetical sequence. Therefore, our results provide a possible explanation for the findings reported by Norman and Fisher. Moreover, a new factor has to be included in the extensive discussions on the topic of computer keyboard design.

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