Continuous priming effects on discrete response choices

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ABSTRACT

When primed by backward-masked, target-like stimuli, discrete responses (e.g. button presses) to simple visual targets can be slower when prime and target match (compatible) than when they do not (incompatible). The current study investigated the nature of the stimulus–response mapping underlying this negative compatibility effect (NCE). Discrete left–right responses to arrow targets were primed with arrows oriented in one of 16 directions. Responses were either a standard button press or a 10 cm movement on a graphics tablet. Both tasks showed an identical NCE; importantly, reaction times in both tasks decreased smoothly as the angular distance between prime and target increased (i.e. as compatibility decreased), with the largest NCE evident between the extreme cases (prime-target distances of 0° and 180°). Primes exerted an effect on the required response in proportion to the amount of overlap (reflecting population vector coding). The mapping between the priming stimulus and response is continuous, not categorical.

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1. Introduction

Masked priming is an experimental paradigm that involves priming a response with a briefly presented prime stimulus followed by a backward mask. Even though the mask usually renders the prime inaccessible to conscious awareness ('subliminal', e.g., Eimer & Schlaghecken, 2002; Schlaghecken, Blagrove, & Maylor, 2008), the prime still influences the motor response to a third, supraliminal target stimulus. In any given trial, the prime can be associated with the same response as the subsequent target ('compatible'), with a different response ('incompatible'), or with no response at all ('neutral'). Priming effects present as either a *positive compatibility effect* (PCE: behavioural benefits on compatible trials and behavioural costs on incompatible trials relative to neutral trials) or as *negative compatibility effect* (NCE: the reverse pattern). The direction of effects (PCE or NCE) depends on factors such as prime visibility or the stimulus-on-set asynchrony (SOA) between prime, mask, and target. PCEs are typically observed when the prime is supraliminal or when the mask-target SOA is very short, whereas NCEs are typically observed with subliminal primes and relatively long (>100 ms) mask-target SOAs (e.g., Klapp, 2005; Schlaghecken, Bowman, & Eimer, 2006; Schlaghecken & Eimer, 2002, 2006; for a review, see Sumner (2007)). With masked primes, the pattern of initial PCEs turning into NCEs with longer SOAs suggests a sequence of activation and inhibition processes in low-level, automatic (not consciously mediated) motor control. Initially, the prime – despite being inaccessible to conscious awareness (REF) – triggers its corresponding motor response, result-

ing in PCEs. Subsequently, this response tendency is inhibited (and its counterpart disinhibited), resulting in NCEs. Although it is generally assumed that the NCE reflects inhibition of the motor response initially triggered by the prime, there is still debate about whether this inhibition arises from self-inhibition of the primed response when the mask removes the evidence supporting it (e.g., Bowman, Schlaghecken, & Eimer, 2006; Klapp, 2005; Schlaghecken & Eimer, 2006; Schlaghecken, Rowley, Sembi, Simmons, & Whitcomb, 2007; Sumner, 2008), from perceptual interactions between the prime and mask (e.g., Lleras & Enns, 2004, 2006), or from the mask itself (e.g., Jaśkowski, 2008; Jaśkowski, Białunska, Tomanek, & Verleger, 2008; Jaśkowski & Przekoracka-Krawczyk, 2005; Verleger, Jaśkowski, Aydemir, van der Lubbe, & Groen, 2004).

1.1. Location of priming effects

While the origin of inhibitory control has generated much controversial debate, the question of where in the visuo-motor system priming effects per se originate has received comparatively less attention. To the best of our knowledge, only three studies have directly addressed this issue. First, Eimer, Schubö, and Schlaghecken (2002) required left and right responses to be made with either the hands or the feet. Priming effects did not transfer from one effector system to the other, suggesting that priming is effector-specific. Next, Schlaghecken, Münchau, Bloem, Rothwell, and Eimer (2003) observed that repetitive transcranial magnetic stimulation (rTMS) of the primary motor cortex affected overall response speed, but failed to alter priming effects. Thus priming effects do not appear to originate in M1. Finally, Schlaghecken, Klapp, and Maylor (2009) mixed circle targets with the usual arrow targets. Circles re-

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quired – in different experiments – a free-choice unimanual response, a no-go unimanual response, or a bimanual response. Arrow primes affected unimanual responses to circle but not bimanual responses, indicating that priming does not affect individual muscle commands. Taken together, these results suggest that priming effects are generated neither at a purely abstract, effector-free level, nor at the level of specific muscle commands, but somewhere between the two extremes. The aim of the present study was to further narrow down the location in the visuo-motor processing stream where priming effects are generated.

1.2. Prime-response mappings

One way to address this question is by investigating the mapping between the prime and the required response in more detail. Priming experiments typically use arrow stimuli to prime and elicit responses (e.g. '≪' for left, '≫' for right). A 'compatible' prime/target pair is therefore the same arrow twice; an incompatible pair uses different arrows. But what if the prime is an arrow oriented at 45°; how would this prime map onto behaviour? There are two plausible ways in which this mapping might be implemented: a reasonably direct, continuous mapping between vision and the motor response, or a more conceptual, categorical mapping in which visual stimuli affect the motor system by virtue of their category membership.

1.2.1. Continuous mapping
One simple solution could be that the prime affects the response in proportion to the extent to the prime overlaps with the imperative stimulus. This would be straightforward to implement via some form of population neuronal coding, which is widespread in the brain (Averbeck, Latham, & Pouget, 2006): if the target set consists of left- and right-pointing arrows, then arrows pointing to the left or right will act as the strongest primes (causing the greatest motor activation), but an arrow pointing, for instance, to the top right will still activate a right motor response to some degree. Specifically, the hypothesis predicts that the strength of motor activation is directly related to the similarity between a given prime and the target set. In other words, the prime impact will vary as a continuous function of prime-target distance.

1.2.2. Categorical mapping
An alternative mechanism could be more categorical in effect: primes might gain access to the motor system if they are members of the target set, but will have no effect if they are not. If the target set consists of left- and right-pointing arrows, then an arrow pointing diagonally upward might not be able to act as a prime at all (although depending on the location of any category boundaries, a prime that is *nearly* left- or right-pointing may have an effect). Regardless, prime impact would not vary continuously, but abruptly; priming would only occur when the prime belonged to the same category as the target. There is some evidence for this requirement: if the target set does not contain any arrows, then arrow primes have no effect on overt behaviour (Eimer & Schlaghecken, 1998; Schlaghecken & Eimer, 2004). However, if the target set contains both arrow and non-arrow stimuli, then arrow primes affect responses to non-arrow targets (Eimer, 1999; Schlaghecken & Eimer, 2004; Schlaghecken et al., 2009).

The question is therefore this: when is a prime compatible with a target? We investigated this issue by using left- and right-pointing arrows as targets, and by using prime arrows that pointed in one of 16 different directions (left, right, up, down, and a further 12 equally spaced directions between these four). A compatible prime is an arrow that is oriented in the same direction as the target arrow (a prime-target angular distance of 0°), and an incompatible prime is an arrow oriented in the opposite direction (a prime-

target distance of 180°). Using an NCE design (masked primes and long mask-target SOA), the former is expected to interfere with the response, making RTs longer, whereas the latter is expected to facilitate the response, making RTs shorter.[1] The question of interest here is how intermediate primes (i.e., with prime-target distances of 22.5°, 45°, 67.5° or 90°) will affect responses: where along the perceptual continuum does a prime change from being compatible to being incompatible with the subsequent target, and is the change in priming effects categorical or continuous?

If compatibility is discrete (categorical), then a prime might only be considered compatible or incompatible over a small range. In this case, longer RTs for compatible and shorter RTs for incompatible trials would be observed for prime-target distances of more or less exactly 0° and 180°, respectively. All RTs to prime-target distances in between these two values would be expected to be constant and intermediate (i.e. all these primes would be effectively neutral). In contrast, if compatibility is a continuous variable, as assumed by the direct-mapping hypothesis, then RT should vary linearly as a function of prime-target distance, smoothly transitioning from slow compatible-trial responses to fast incompatible-trial responses via an intermediate, neutral RT.

1.3. Spatially extended responses

One might argue that even if the intermediate primes directly activated the motor system, these activations might be too small to be easily detected in a task that requires an extremely restricted response such as a simple key press. Therefore, the present experiment was conducted once using the standard key-press task, and once using an extended movement executed on a graphics tablet.

Recent work by Schmidt (Schmidt, 2002; Schmidt, Niehaus, & Nagel, 2006; Schmidt & Seydell, 2008) has begun to investigate response priming of continuous movements. In these experiments, participants moved their fingers from a home location to a location 54 mm away, indicated by a colour target. Targets were preceded by (and acted as masks to) compatible or incompatible colour primes. The studies thus employed a PCE design (mask-target SOA of 0 ms), and PCEs were indeed observed in both RT and trajectories (participants were more likely to make a move initially in the wrong direction, then smoothly correct themselves). To the best of our knowledge, the present experiment is the first to investigate whether with the appropriate design, it would also be possible to obtain NCEs in a spatially extended movement.

The aim of the current study thus is twofold:

(a) to investigate the impact of primes varying along a continuous dimension (direction) on responses to discrete targets, and
(b) to directly compare these effects under two response modalities (key-press response versus extended movement), to investigate whether priming effects in a larger movement differed in any detectable way from the standard NCE reliably found with key-press tasks.

2. Methods

2.1. Participants

There were 22 participants in the button task (11 males, 11 females, all but four right-handed, age range 18–40, median age

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20 years) and 20 different participants in the tablet task (three males, 19 females, all but two right-handed, age range 18–20, median age 19 years). Two additional participants were excluded from the tablet condition (one for a high (~50%) error rate and one for missing data due to a technical fault). All participants had normal or corrected-to-normal vision.

2.2. Design

There was one between subject factor, response type (two levels: button, tablet) and one within subject factor, prime-target distance (nine levels: 0° [compatible], 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°, 180° [incompatible]).

2.3. Apparatus

Both experiments were run on a desktop PC. Stimuli generation and presentation, as well as data collection and offline data analysis, was controlled by a custom suite of Matlab software, the Masked Prime Toolbox (MPT; Wilson, Tresilian, & Schlaghecken, submitted; the MPT is open source and available online at http://www.fbs.leeds.ac.uk/staff/Wilson_A/MaskedPrimingToolbox.zip). The MPT incorporates the Psychophysics Toolbox (http://psych-toolbox.org; Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). Button press responses were recorded using a standard qwerty PC keyboard; tablet responses were recorded using an A0 Wacom intuos[2] graphics tablet, which reports position data at 100 Hz (see Fig. 1a for a picture of the tablet set-up).

2.4. Procedure

The visual stimuli were identical in both Response conditions – refer to Fig. 1b for examples and a timeline of each trial. Primes, masks and targets were all presented in the centre of the screen. Primes and targets were double arrows (e.g. ≫), 18×10 mm (~$1.21° \times 0.67°$ visual angle at the viewing distance of ~85 cm). Primes were oriented in 16 directions spaced at 22.5° intervals. Targets were either arrows pointing left or right. Primes were presented for 33 ms (two frames at 60 Hz), targets were presented for 100 ms (six frames at 60 Hz). A unique random mask was generated for each trial to prevent perceptual learning of the mask (Schubö, Schlaghecken, & Meinecke, 2001) and minimise perceptual interactions between prime and mask features (e.g. Schlaghecken & Eimer, 2006). Each mask was 30×21 mm (~$3° \times 2.1°$ visual angle) and consisted of 70 lines arranged in a roughly rectangular grid. Each line had a normally distributed random length (mean 15 pixels, SD 2 pixels) and width (mean 4 pixels, SD 2 pixels). Masks were presented for 100 ms (six frames at 60 Hz).[2] There were 16 prime orientations and two responses, and therefore 32 unique trial combinations. In 10 blocks of 64 trials, each combination was repeated twice, in randomised order.

In the button task, responses were made by pressing the 'a' key if the arrow was pointing to the left, and the 'l' key if the arrow was pointing to the right. The software detected the key press and recorded a reaction time and whether the response was correct or incorrect (RTs less than 100 ms were counted as errors; total errors were 4.6% of trials). The participant was instructed to respond as quickly but as accurately as possible.

In the tablet task, each new trial was triggered when the participant had placed the stylus in the centre 'home' location and held it

there for 0.5 s. 'Home' was a 1 cm^2 box in the centre of the tablet, specified by an orange marker (Fig. 1a). This was necessary to ensure that all trials began from a canonical start location. If the target was a left-pointing arrow, participants moved from the start location to a plastic bar located 10 cm to the left of centre; if it was a right-pointing arrow, they moved to an equivalent bar 10 cm to the right. This bar meant that participants always moved an appropriate distance without needing to visually fixate the stylus, i.e., they were able to respond quickly while still looking at the display. Participants were instructed to respond as quickly and as accurately as possible, and that if they initially headed in the wrong direction, to end up in the right location.

2.4.1. Computing tablet reaction times

On each trial, Matlab recorded a 100 Hz x position time series synchronised to the display such that time = 0 was equal to the onset of the prime. Each time series was normalised by subtracting out the initial position and filtered with a dual-pass Butterworth filter using a cut-off frequency of 20 Hz. The filtered data were numerically differentiated to yield a speed time series. Movement onset time (MOT) was computed from these data using a standard recursive algorithm which detects the time point in the speed time series when movement speed reliably crosses a threshold value, relative to the variability of the signal (Teasdale, Bard, Fleury, Young, & Proteau, 1993). Reaction time (RT) was computed as MOT minus target onset time. To score a response as correct or incorrect, the first 10 normalised data points after movement onset (i.e. covering 100 ms) were averaged. The sign of this average indicated whether the initial movement was to the left or to the right; this was compared to the correct answer. Any computed RTs of less than 100 ms were also discarded as errors (total errors were 13.2% of trials, 1.2% for being too fast).[3]

2.5. Data analysis

The question under investigation was how RT changed as the prime moved from being 0° away from (compatible with) to 180° away from (incompatible with) the target. The 32 conditions were therefore coded in terms of angular prime-target distance, mod 180°[4]. Two of these 32 prime-target pairs (left prime/left response and right prime/right response) were 'compatible', i.e. a prime-target distance of 0°; two (right prime/left response and left prime/right response) were 'incompatible', i.e. a prime-target distance of 180°. The remaining 28 prime-target pairs were distributed across seven prime-target distances (22.5°, 45°, 67.5°, 90°, 112.5°, 135°, and 157.5°), four per condition. All four pairs within a condition therefore had primes and targets that were a set distance away from each other (e.g. the 45° distance condition included left responses to primes oriented 45° and 315° and right responses to primes oriented 135° and 225°).

3. Results

3.1. Negative compatibility effect

We first confirmed that there was a negative compatibility effect (NCE) in the button and tablet RT data (Fig. 2). We performed a repeated measures ANOVA on the RT data from the 0° (compatible) and 180° (incompatible) distance conditions, with response

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[2] In a pilot study with 15 participants, similar conditions resulted in a correct prime identification of 46.7% in a 2-alternative forced choice task. This value was not significantly different from 50% chance level, $t(14) < 1$, $p > .5$, confirming that the present set-up produces prime visibility near or below the threshold of conscious perception.

[3] Note that Eimer and Schlaghecken (2001) reported higher error rates for eye movement responses – which can be regarded as a type of extended and less restricted movement – as compared to manual key-press responses.
[4] Analysis confirmed there were no asymmetries in the space; primes oriented between 0° and 180° were treated the same as the matching primes oriented between 180° and 360°.
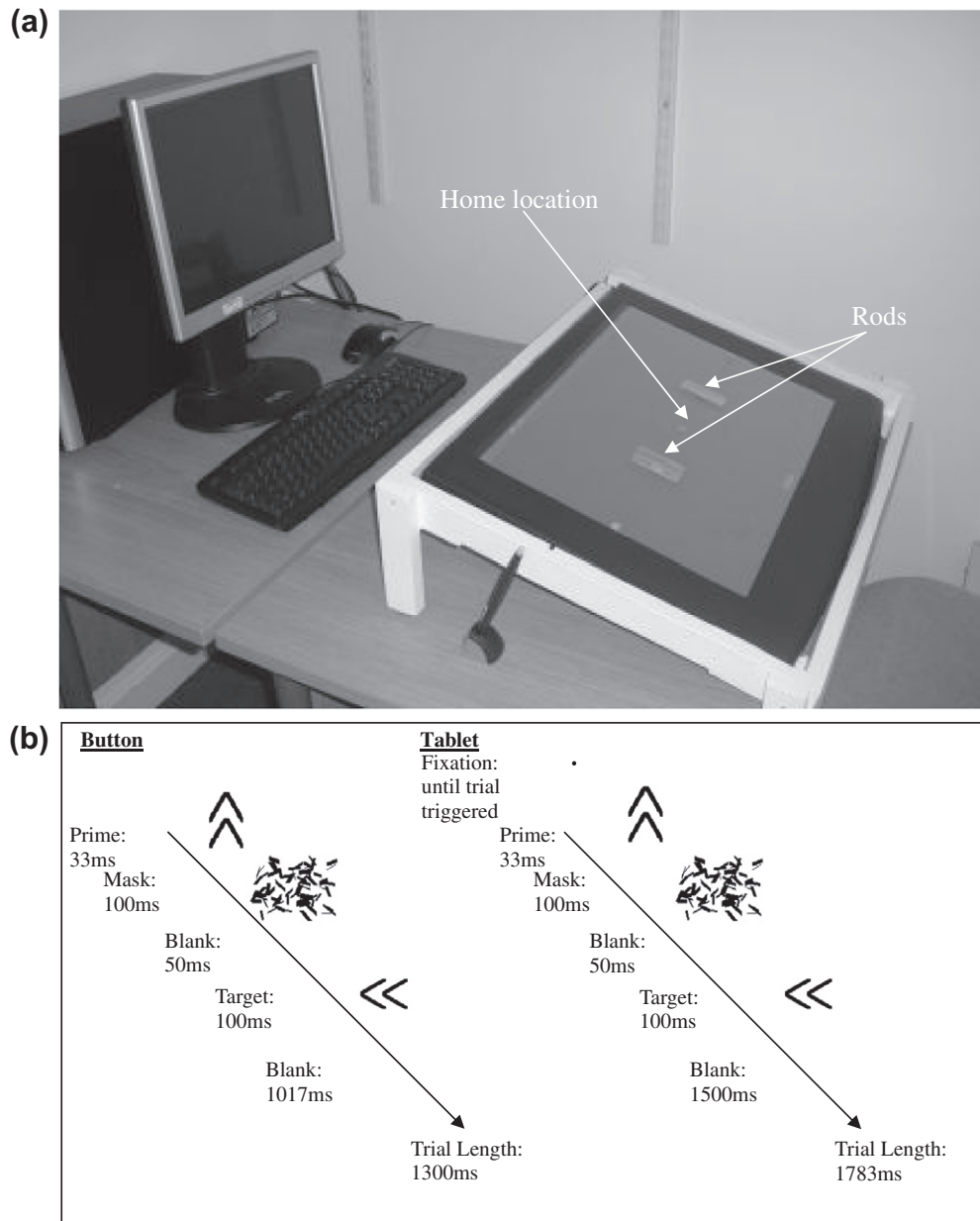
(a)

(b)

Fig. 1. (a) Picture of the tablet set-up. The 'home' location was indicated by the orange marker in the centre of the screen, and the movement was constrained to 10 cm in either direction by the plastic rods. (b) Timeline of the experiments. The button trials were paced independently from the participant and lasted 1300 ms; Tablet trials were triggered by the participant moving the stylus onto a specific 'home' location on the tablet, and there was a constant 1500 ms data collection period for a response.

type as a between subjects factors and compatibility as a within subject factor. Compatible responses were slower than incompatible responses, $F(1, 40) = 58.1$, $p < 0.001$, partial-$\eta^2 = 0.60$, and (unsurprisingly) tablet response were much slower than the more straightforward button presses, $F(1, 40) = 32.5$, $p < 0.001$, partial-$\eta^2 = 0.45$. Importantly, there was no interaction, $F(1, 40) = 0.71$, $p = 0.405$, partial-$\eta^2 = 0.02$, indicating that the NCE did not differ across response type.

3.2. Prime-target angular distance

We performed a repeated measures ANOVA on median RTs from each response type and all nine distances (Fig. 2). In addition to the main effect of response type, $F(1, 40) = 34.1$, $p < 0.001$, partial-$\eta^2 = 0.46$, there was a main effect of distance, $F(8, 320) = 33.8$, $p < 0.001$, partial-$\eta^2 = 0.46$, with RTs decreasing linearly in both

response conditions from the compatible to the incompatible extremes. Crucially, there was again no significant interaction, $F(8, 320) = 0.792$, $p = 0.610$, partial-$\eta^2 = 0.02$, indicating that the effect of distance was the same in both response conditions.

To probe the main effect of distance, we fit each data set with a separate linear regression. The button RTs had a slope of -3.87 ms ($R^2 = 0.97$; $t(8) = 15.2$, $p < 0.01$), and the tablet RTs had a slope of 4.24 ms ($R^2 = 0.83$; $t(8) = 6.2$, $p < 0.01$). This supported the main effect/no interaction ANOVA pattern: each distance condition corresponded to an approximately equivalent RT saving (~4 ms) in both response conditions.

3.3. RT distributions

The effect of the prime on RT was a continuous, linear function of prime-target distance, supporting the continuous mapping
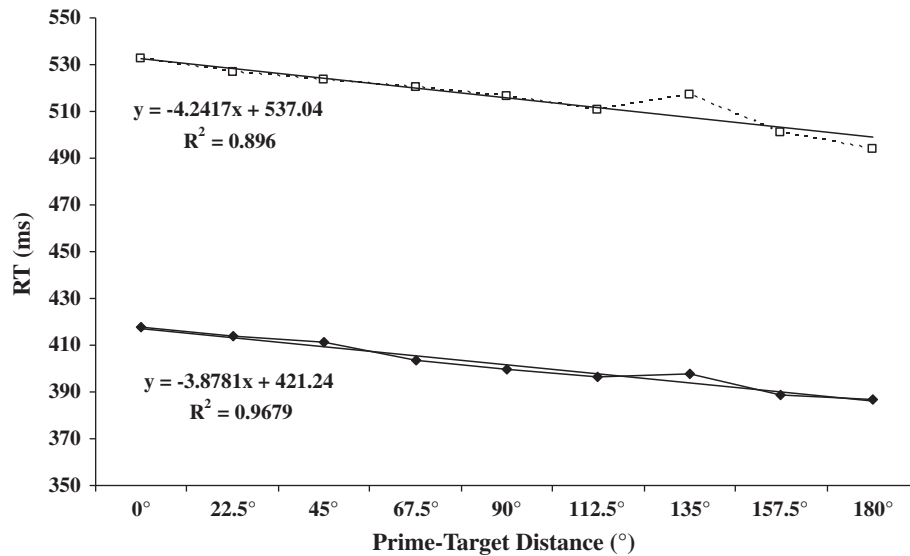
Fig. 2. Reaction time (RT) data from both experiments (tablet: open squares/dotted lines, button: filled diamonds/solid line) plotted as a function of prime-target angular distance. There was an identical negative compatibility effect in the two conditions, with longer RTs in the 0° (compatible) condition relative to the 180° (incompatible) condition. RT moved from one extreme to another as a linear function of distance, with a slope of approximately 4 ms in each condition.

hypothesis. One caveat is that it is theoretically possible to obtain such a linear relationship between prime-target angular distance and priming effects from a categorical mechanism, provided the linear increase in prime-target distance led to a corresponding change in the *probability* that the prime had a certain effect. From 0° (compatible) to 90°, the prime would have a decreasing probability of interfering with the response; from 90° to 180° (incompatible), the prime would have an increasing probability of facilitating the response. This hypothesis predicts that the RT distributions in the 0° (compatible) and 180° (incompatible) conditions would be unimodal, with different modes, and the intermediate distributions would move from one to the other via a bimodal intermediate at 90°. One mode would represent trials in which interference occurred ('pseudo-compatible' trials), the other in which interference occurred ('pseudo-incompatible' trials).

The continuous mapping hypothesis makes a different prediction, specifically that RT distributions should remain unimodal with the mode shifting smoothly towards faster RTs as the distance increases. This is because this hypothesis assumes prime impact is varying continuously with distance.

We therefore examined the three extreme distance conditions: 0°, 90° and 180°. In order to compare these three conditions across both response types, data were z-transformed. Within each response condition, each RT was converted by

$$z(\mathrm{RT}_{trial}) = [\mathrm{RT}_{trial} - \mathrm{average}(\mathrm{all}\ 0°, 90°, 180° \mathrm{data})]$$
$$/\mathrm{SD}(\mathrm{all}\ 0°, 90°, 180° \mathrm{data})$$

and the z scores were sorted into three latency bins – faster-than-average responses (z scores < −0.5), average responses (z scores between −0.5 and 0.5) and slower-than-average responses (z scores > 0.5). These data are plotted in Fig. 3. The continuous mapping hypothesis predicts that the proportion of fast and slow responses should change linearly with increasing prime-target distance, while the categorical mapping hypothesis predicts a non-linear change in these proportions. Fig. 3 clearly shows the former, thus indeed supporting the continuous mapping hypothesis: the linear change in RT with increasing prime-target distance is caused by the prime becoming less likely to interfere with the response while becoming equally more likely to facilitate the response.

4. Discussion

The present experiment asked whether subliminal primes have a continuous or categorical effect on later responses. We investigated this by priming one of two responses (left vs. right) with one of 16 primes (arrow heads differing in orientation, mapping out a full 360° – circle in sixteen 22.5° – steps). Two types of response (button pressing and a 10 cm extended movement) showed the negative compatibility effect (NCE; Eimer & Schlaghecken, 1998). Furthermore, reaction times (RT) varied as a linear function of prime-target distance, transitioning smoothly from slowed compatible trials to facilitated incompatible trials. Thus the impact of the prime – and hence the prime/target compatibility – changes continuously, not categorically, between these two extremes (at least along the dimension of orientation). These results are consistent with the idea that visual input is mapped directly onto motor responses represented in the form of neural population vectors, thus supporting the direct parameter specification account (e.g., Neumann, 1990), which assumes that under certain conditions, sensory information can be used for the direct control of action without 'representational' (conscious and categorical) mediation;.

The present results would indeed be predicted by population coding theories. Single neurons cannot encode useful information; population activity is required to encode functionally relevant perceptual and motor parameters. This encoding principle is assumed to be widespread in the cortex (Averbeck et al., 2006). Population codes generally vary continuously along their dimension of interest, for instance population coding of movement direction in M1 entails smooth changes in the preferred direction of populations of neurons (Georgopoulos, Schwartz, & Kettner, 1986). The present experiment demonstrated a continuous effect of the prime even though the response set was well defined in advance as one of two discrete options. Population coding suggests that a parameter such as direction is always specified as a vector representing the net result of the contributions of differently tuned neurons. Consequently, the greater the similarity of a prime to a specific directional target, the larger the proportion of neurons representing this target that will become activated. As the subsequent inhibition will conceivably affect only activated neurons, the
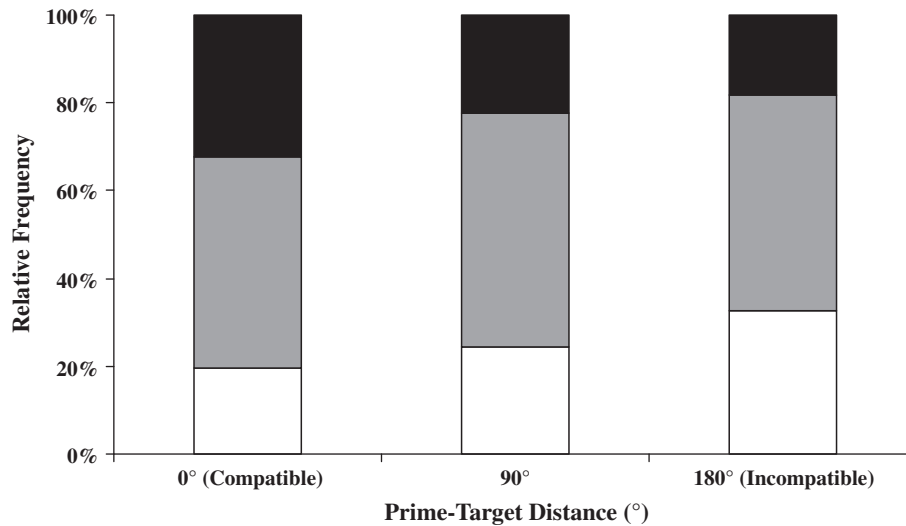
Fig. 3. Relative frequency of the *z*-transformed reaction time (RT) data from both the button and tablet conditions. The relative proportion of faster-than-average responses (*z* scores <−0.5: white bars) increases smoothly from 0° to 90° to 180° prime-target distance, and the relative proportion of slower-than-average responses (*z* scores >0.5: black bars) decreases smoothly. This shows that the linear change in RT with increasing prime-target distance arises from a linear change in prime strength, rather than a non-linear change in the probability a trial is primed. See the text for more details.

behavioural consequence is that the magnitude of the NCE varies as a function of the degree to which primes are part of the S-R set.

Earlier findings (Schlaghecken et al., 2003) indicate that the critical neural substrate for these activation and inhibition processes is not M1. Furthermore, evidence from neuroanatomy (e.g., Margulies et al., 2009) and from patient studies (e.g., Karnath & Perenin, 2005) suggests that the precuneus is crucially involved in the fast control of visually guided actions, and might in fact be the earliest processing stage of cortical visuo-motor integration. We tentatively suggest that priming effects in the masked prime paradigm might originate as early as the precuneus, and from there are relayed forward to supplementary and finally primary motor cortices. In this context, it is worth noting that the present data pattern is strikingly reminiscent of the linear relationship between RTs and a stimulus' angular displacement in mental rotation tasks, which are also thought to involve the precuneus (especially in participants employing an automatic or bottom-up strategy, e.g., Butler et al., 2006; Zacks, 2008).

We also directly compared performance across two types of response – the traditional button press with fingers of the left or right hand, and also a 10 cm left or right movement using one hand. The only difference between the two response times was that the latter were slower (a result readily accounted for by the straightforward differences in the response execution requirements – see below). The pattern of RT data was otherwise identical between the two responses – similar slopes to the linear change in RT with prime-target distance, and similar standardised distributions.

This result adds to the literature supporting the hypothesis that the NCE is not restricted to a very limited set of artificially restricted motions. Eimer and Schlaghecken (2001) replicated the NCE using manual, saccadic and vocal responses. Klapp and Hinkley (2002) showed that the NCE occurs for both the standard left–right responses using two hands and up–down responses using fingers of the same hand, while Schlaghecken et al. (2006) elicited the NCE with one finger of one hand producing one of either two or four response alternatives. The tablet response extends these findings to yet another class of response, implemented using different neuromuscular elements in a distinct coordination. The essentially identical nature of the NCE pattern using the tablet as compared to the button press is further strong evidence that it results from identical processes in either case.

The fact that the RT distribution for the tablet responses was identical to that of the button presses means that this task is a suitable method to extend the research on the effects of masked primes on the preparation of movements to other parameters. Movement execution requires more than simple response selection. Once a given response has been selected it must be *parameterised*, i.e. the abstract must be made concrete and specific. The initial selection is effectively discrete, for instance, left vs. right hand. Response parameters are, in general, continuous variables such as force, amplitude, and direction, and the same basic response (e.g. a left press) can be executed in many different ways (e.g. varying levels of force). Button pressing is therefore a useful task because it is highly constrained – the various possible parameters can only take a small number of values and hence the overall response preparation time is fast (one reason why RTs were faster overall in the button pressing task here). But these constraints mean button pressing cannot be used to investigate how these parameters are specified, and what influences their specification. A less constrained, spatially extended movement (such as the left or right movement measured by the tablet in the current experiment) is more suited for this, as it leaves several response parameters more free to vary (e.g., Favilla, Hening, & Ghez, 1989; Ghez et al., 1997).

Priming may or may not influence continuous response parameters in the same way as it affects overall response selection. There are three basic characteristics of response selection that are assumed to be at work in the NCE paradigm: (1) more than one candidate response can be active at any one time, (2) these alternatives are mutually inhibitory so that a 'winner' can emerge quickly, and (3) each candidate can self-inhibit if it is activated inappropriately. There is some empirical support for the notion that multiple movement parameters can be held simultaneously and that these are mutually inhibitory (see Erlhagen & Schöner, 2002 for a discussion), but there is as yet only preliminary evidence for self-inhibition and this is not included in any current models of movement parameterisation (e.g. topographical population coding of movement direction or distance; Georgopoulos et al., 1986). However, preliminary evidence comes from two experiments in which the response varied in direction and still produced an NCE (eye movements left or right, Eimer & Schlaghecken, 2001; moving the finger of one hand left, right, up or down; Schlaghecken et al., 2006). These studies are limited, however, because the experimen-

tal variation of response direction was constrained to be categorical. There is a clear need for more research on this topic, and the current data support the validity of the tablet task; this would allow continuous variation in response direction in the same way we were able to vary prime orientation here.

On a more general note, it might be interesting to note that the present methodology could readily be used to probe the issue of compatibility in any number of priming paradigms. This issue is almost never addressed directly, and although the operational definitions of compatibility used across various priming paradigms are not in themselves questionable, variations make it difficult to compare results across experiments. This is less of a problem for priming studies involving stimuli such as arrows etc., where the variation is minimal. However, for priming studies of language, for instance, the issue is key. Definitions of semantic compatibility (or more commonly, *relatedness*) vary greatly across studies (Hutchison, 2003; Lucas, 2000). Relatedness can be category membership (e.g. Neely, 1977), number of shared features (e.g. McRae & Boisvert, 1998), or what emerges from a free association task (e.g. Bleasdale, 1987; Williams, 1996), making it all but impossible to compare studies. In principle, at least, the current protocol could easily be adapted; all that is required is at least one dimension along which relatedness is defined, and stimuli drawn from all along this dimension. As shown by the present study, the data are of both methodological and theoretical interest, and provide information about the appropriateness of the dimension and as well as organisation along it.

In sum, the current experiment demonstrated that, for arrow stimuli, the NCE represents two extreme ends of a linear continuum. Reaction times varied continuously with prime-target distance. These data support the hypothesis that primes directly activate the motor system, without a mediating categorical/conceptualisation process. Results thus shed light on what constitutes a compatible vs. an incompatible prime-target pair and why. The methodology could in principle be adapted to investigate any continuous stimulus dimension, and the results are informative about both whether that dimension matters, and how.

Acknowledgments

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