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Show some sensitivity! Using motion tracking to explore unconscious processes

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Abstract

Although invisible to us, unconscious stimuli were shown to still affect our behavior. However, the field of unconscious processing abounds with contradicting findings, which in turn evoke an ongoing controversy about the scope of such processing, and specifically for semantic effects. Such contradicting results can be explained by methodological limitations of some of these studies. One possible limitation, that is studied in this thesis, might be an underestimation of unconscious processing due to the use of insensitive measures of the unconscious effect. The most prominent measure for probing unconscious effects is reaction time (RT), as measured using keyboard presses. However, this effect is usually very small and indexes the final decision but not the process of formulating it. Both problems might be solved by using motion tracking, which has become a popular tool for unraveling cognitive processes.

But is motion tracking indeed more sensitive to unconscious effects than a keyboard? To date, only one study directly made this comparison and found that the unconscious effect was marginally significant when probed with a keyboard, but robust when measured via mouse tracking. However, this study suffers from several limitations, both with regards to its awareness measurement and to its motion tracking measure. The current thesis is aimed at testing the hypothesis that motion tracking might be superior to keyboard responses in detecting the effects of unconscious processing, while overcoming the aforementioned limitations.

To do so, rigorous awareness measures and an intuitive reaching response were used in a series of four studies. Three exploratory studies were aimed at finding the optimal conditions for discovering an unconscious effect when using reaching responses. A fourth confirmatory study directly compared between motion tracking and keyboard responses. All four studies used a priming paradigm that followed a classical study by Dehaene and colleagues (2001), in which subjects performed a semantic judgment on a target word that was preceded by an identical/different invisible prime. The first experiment produced only marginally significant results, presumably because it allowed for slow responses. The second experiment reduced this limit and divided it to onset time and movement duration as well as introduced another training block to improve response speed. Unfortunately, a high proportion of trials were excluded due to problematic response timing. Therefore, the third experiment incorporated a separate training day to improve the response speed. Although the proportion of excluded trials did not diminish, a marginal congruency effect was found. In the fourth experiment I discarded the training day and

included both a reaching task and a keyboard task. Both measures produced a congruency effect which, combined with the rigorous awareness testing, provided substantial evidence for the existence of unconscious word processing that cannot be easily refuted. Contrary to previous findings, the unconscious effect in the motion tracking task was not larger than in the keyboard task. Suggested augmentations to the paradigm are discussed which could improve the motion tracking's sensitivity even further.

Introduction

Our brain continuously processes information. It receives inputs via our senses and processes it in various ways, for a variety of stimuli and using different modalities (Kanwisher et al., 1997; Kappers & Bergmann Tiest, 2013; Poirier et al., 2005; Willander & Larsson, 2006). For example, upon seeing a ball flying our direction, we process its trajectory and the likelihood of it hitting us. The produced results can lead to a change in behavior – like ducking the ball in this case (Aivar et al., 2008; von Hofsten & Lindhagen, 1979) – and/or to internal changes, like the induction of fear (Sawchuk et al., 2002; Siedlecka & Denson, 2019). Some of these processes are also accompanied by conscious experiences (Brown et al., 2019; Lamme & Roelfsema, 2000; Mashour et al., 2020; Tononi et al., 2016): I perceive the flying ball, and I experience the sense of fear. But this is not always the case: I might miss the ball altogether, for example if I am extremely occupied by a different engaging task (Hyman et al., 2009; Mack & Rock, 1998). Importantly however, I might still duck the ball following some automated response triggered by unconscious processing (Holland et al., 2005; Kihlstrom, 1987; Kouider & Dehaene, 2007).

What differentiates between such conscious and unconscious processing? In the lab, studies try to answer this question by using different methods to render a stimulus invisible (for a review, see Breitmeyer, 2015; Kim & Blake, 2005). One such method degrades the physical properties of the stimulus (e.g., contrast, resolution, volume, duration; Daltrozzo et al., 2011; Li et al., 2007). Another suppresses the stimulus by presenting a much more salient stimuli concurrently with the critical stimulus or at close temporal proximity to it (e.g., masking, CFS), hereby rendering it invisible (Almeida et al., 2013; Dehaene et al., 1998). Invisibility can also be achieved by diverting attention away from the stimulus (Hyman et al., 2009; Mack & Rock, 1998).

All three methods, and others typically decrease the visibility of the stimulus, but also evoke weaker neural responses to the stimulus (Dehaene et al., 1998; Yuval-Greenberg & Heeger, 2013). Such weak signals usually translate to small behavioral changes that are hard to detect (Greenwald et al., 1996). As a result, the field abounds with contradicting findings (Hesselmann & Knops, 2014; Kouider & Dehaene, 2007; Moors et al., 2016; Peters & Lau, 2015), which in turn evoke an ongoing controversy about the scope of unconscious processing (Hassin, 2013; Hesselmann & Moors, 2015; Peters et al., 2017).

Contradicting findings

One point of disagreement concerns the extent of semantic processing without awareness (Abrams et al., 2002; Damian, 2001). Among other paradigms, it has often been studied using priming (Kouider & Dehaene, 2007). In a priming paradigm, the participant is asked to perform a certain task on a target stimulus (e.g., classify as word/non-word) that is preceded by a related/unrelated invisible prime stimulus. Typically, the participant's response is either facilitated or inhibited according to the congruency between the prime and the target. Such a congruency effect is often taken as evidence the prime was indeed processed (e.g., Abrams et al., 2002; Finkbeiner et al., 2004). To ensure that the prime was indeed invisible, a subjective and/or objective measure of prime awareness is typically administered (Reingold & Merikle, 1988; Sandberg et al., 2010). For the subjective measure, the participant is asked to report about her perception of the prime by rating how well she saw it on a categorical scale that ranges between "did not see anything at all" to "saw the prime clearly" (the Perceptual Awareness Scale; PAS; Sandberg & Overgaard, 2015). Using a subjective measure allows to detect awareness on a trial-by-trial basis, yet it is subjected to the criterion problem, where participants' ratings might be highly affected by their response criterion (Eriksen, 1960; Hannula et al., 2005). For the objective measure, the participant is asked to make an objective judgement about the prime, typically choosing an answer among several options (i.e., a forced choice question). If the proportion of correct responses across trials (or the overall sensitivity, measured using d'; Macmillan & Creelman, 2004) is higher than chance, the stimuli will be considered as consciously perceived. This measure is less affected by the criterion problem, yet it is held to overestimate conscious perception (Bowers, 1982; Merikle & Reingold, 1998).

While some semantic priming studies found that invisible words can be processed up to the semantic level (Dell'Acqua & Grainger, 1999; Naccache & Dehaene, 2001), opposing studies failed to show semantic effects and claimed that processing only reaches the lexical level (Shelton & Martin, 1992). Other studies have not found any congruency effects (Heyman & Moors, 2014; Pratte & Rouder, 2009). Similar controversies revolve around other types of processing: claims for arithmetic computations being performed without awareness (Karpinski et al., 2019; Sklar et al., 2012) were challenged by failures to replicate (Moors & Hesselmann, 2018, 2019), and a similar mixed picture emerged also for studies of processes like integration (Mudrik et al., 2014; Mudrik & Biderman, 2017).

Explaining The Discrepancy between Findings

How can these contradicting results be explained? One option, that is explored in this thesis, is that they stem from methodological limitations of some of these studies. For example, the way consciousness is measured might strongly affect the obtained results: if the awareness measure is not sensitive enough to discover residual awareness, the researcher might falsely attribute unconscious processes to conscious processing (Sand & Nilsson, 2016). Such insensitivity can occur if the objective task probes features of the stimulus that are irrelevant for the performance in the main task (Merikle, 1992; Newell & Shanks, 2014; however, note that this could also lead to overestimation of awareness; Michel, 2022). In addition, introducing a long delay after the presentation of the subliminal stimulus might cause the memory of it to fade before it is queried by the awareness measure (Lagnado et al., 2006; Newell & Shanks, 2014; Ogilvie & Carruthers, 2014). Underestimation of awareness can also occur if the participant uses a very strict criterion when judging whether she saw the prime (Eriksen, 1960; Hannula et al., 2005; Peters & Lau, 2015). Finally, if the objective task is too difficult, participants can be at chance even if they do see the stimulus, or parts of it, and their motivation to perform the task on invisible stimuli can also be reduced, leading to worse performance (Pratte & Rouder, 2009).

The above issues might lead to overestimating unconscious processing, due to contamination by conscious effects, but one might also underestimate unconscious processing, due to insensitive measures of the unconscious effect. The most prominent measure for probing unconscious effects is reaction time (RT), as measured using keyboard presses (e.g., comparing RTs in the congruent vs. incongruent condition; Naccache et al., 2002; Naccache & Dehaene, 2001). However, for invisible primes this effect is usually very small (Greenwald et al., 1996). Also, it only indexes the end result of the response, and does not provide insight on the process of formulating the final decision as it unfolds over time (Scherbaum et al., 2010).

Comparing Motion Tracking with Keyboard Response

Both these problems can be solved using motion tracking, which has become a popular tool for unraveling cognitive processes (Freeman et al., 2011), and might prove to a be a powerful tool for detecting effects evoked by unconscious processes. Contrary to keyboard RTs, which produce a discrete value for each trial, motion tracking provides a continuous set of values which is better suited for tracking ongoing cognitive processes. This was previously used in other fields of research (e.g., unraveling the temporal dynamics of speech comprehension, to show that words are processed in an incremental manner; Spivey et al., 2005). Such online tracking of movement as the cognitive processes take place provides further insight on their development over time. For example, when studying syntactic speech processing, researchers used motion tracking to demonstrate that multiple syntactic interpretations of a sentence are processed simultaneously as opposed to serially (Farmer, Cargill, Hindy, et al., 2007). Similarly, motion tracking allows one to compare movement patterns associated with simultaneous conflicting goals and serially occurring goals (Farmer, Cargill, & Spivey, 2007; Freeman et al., 2008). Finally, the rich, continuous data afforded by motion tracking can be curated for various parameters that are not available when using non-continuous measures, and might reveal an effect that goes unnoticed in the latter case. One such parameter is velocity which was used to inspect participants' confidence in their answers (Dotan et al., 2018). Another parameter is Changes of Mind (COM), that are not possible when responding with a keyboard, but are reflected in the trajectory when using motion tracking (Resulaj et al., 2009; Song & Nakayama, 2009).

Previous Priming Findings Made with Motion Tracking

The ability to unravel cognitive conflicts and observe COM might be beneficial when studying unconscious processing, especially in priming paradigms that evoke conflicts between the prime and target. This was indeed done in a handful of studies: two studies probed the level at which unconscious images are processed by asking participants to classify a target image preceded by an invisible prime as a person / animal using a reaching response, while movement was tracked. When the prime was incongruent with the target, reaching trajectories tended to deviate towards the incorrect answer (Experiment 1 in Finkbeiner & Friedman, 2011), therefore indicating that the semantic meaning of prime images was processed unconsciously (Finkbeiner et al., 2008; Friedman & Finkbeiner, 2010). In a similar experiment digits or letters were primed before classifying a target stimulus as one of them, and here too the trajectories were affected by the congruency between the prime and the target (Experiment 2 in Finkbeiner & Friedman, 2011). Finally, another study used motion tracking to demonstrate the role of attention in facilitating priming: when participants judged a target digit as larger or smaller than 5, longer reach trajectories were observed when this target was preceded by an incongruent prime (compared to a congruent one), and this effect was larger when the participants attended to the prime (Xiao & Yamauchi, 2015).

Thus, motion tracking can be used to unravel unconscious processing as it unfolds but are these effects indeed stronger than keyboard-RT ones? This question has hardly been studied. Two experiments combined motion tracking and keyboards RTs, yet without directly comparing between them. In the first, a prime arrow pointing to the left/right/neutral direction was rendered invisible with meta-contrast masking, and participants were asked to choose to which side was the mask pointing. The task was first performed with a keyboard, revealing that prime-target congruency affects the response speed, and then with stylus tracking. In the stylus session, the stimulus was presented only after the participants initiated a movement towards the center, forcing them to correct their movement mid-way. The correcting movement's onset, length and velocity were influenced by the prime-target congruency which gave rise to the conclusion that subliminal stimuli can influence the ongoing execution of an already-prepared target-directed movement (Cressman et al., 2007). In the second study, the effect of unconscious dorsal – as opposed to ventral – processing on decisions was examined using a subliminal priming paradigm. Primes and targets were images of animals/tools that belonged to the same/different semantic category and had a similar/different shape (i.e., elongated / round), and therefor similar/different affordances. When responses were given via a keyboard, semantically congruent primes improved the response speed to the subsequent targets. While keyboard responses reflected a semantic priming effect, reaching movements, which were assumed to depend more heavily on dorsal processing, were used to examine if the dorsal stream elicits subliminal shape-related effects. Indeed, blob-like animal primes caused a larger deviation from the elongated tool target compared with elongated animals. The researchers accordingly concluded that dorsal-stream processing contributes grasp related information to decision making processes (Almeida et al., 2014).

To date, only one study directly compared the strength of the effects revealed by keyboard presses and motion tracking (Xiao et al., 2015). In this study, participants classified two digits as identical/different by either pointing to the correct answer with the mouse or choosing it with the keyboard. The target digits were preceded by a positive/negative subliminal image which facilitated same/different responses, respectively. Critically, this effect was marginally significant when probed with a keyboard, but robust when measured via mouse tracking. Although this study indeed reinforces the above assumption, according to which motion tracking might be beneficial for unraveling unconscious processes, it also suffers from several limitations. First, awareness assessment was done in a separate block after the main task, with no online assessment of prime visibility on a single trial level. This is especially important since the visibility ratings of many participants were above zero, suggesting that the effect might have been driven by some conscious processing. In addition, performance was not tested against chance, and was instead shown not to correlate with the congruency effect – a method that has been widely criticized (Malejka et al., 2021). Finally, the number of trials in the awareness task was 96, which might be underpowered for detecting awareness according to unpublished work our lab.

Notably, this study used mouse tracking, which might be less sensitive than reaching movements. Using a mouse requires participants to remap the real-world representation into 2D. Such 2D mapping constrains free movement (Desmurget et al., 1997), which can affect the trajectory and timing of the movements (Palluel-Germain et al., 2004) and suppress the expression of cognitive conflicts. Indeed, when both measures were compared, reaching produced shorter movement durations, larger curvatures, faster velocities and most importantly, it responded faster to changes of mind (Moher & Song, 2019). Reaching movements are also more intuitive than using a mouse, making them less effortful and possibly more likely to express fluctuations in the decision (Burk et al., 2014; Moher & Song, 2014). These properties accordingly suggest that reaching movements might be optimal for detecting fast and short-lasting processes such as unconscious priming effects (Greenwald et al., 1996).

Current Research

The current study was aimed at testing the above hypothesis that motion tracking might be superior to the commonly used keyboard responses measure in detecting effects of unconscious processing. This was tested here using rigorous awareness measures to ensure residual awareness is not mistaken for unconscious processing. Three pilot experiments were aimed at finding the optimal conditions for discovering an unconscious effect when using reaching responses. A fourth confirmatory experiment directly compared between motion tracking and keyboard responses as a means to examine if one measure has an advantage over the other. All four studies used a priming paradigm following a classical study by Dehaene and colleagues (2001), in which participants were presented with a masked prime word followed by a visible identical/different target word. This task was chosen as it was supposed to evoke strong effects, in a fairly simple design which probes identity priming. The participants were asked to perform a semantic judgment on the target word to determine if it describes a natural or artificial item. In the first three experiments, I expected to find evidence for a congruency effect with motion tracking, so that the average reaching trajectories of the incongruent trials would deviate towards the incorrect answer further than would the trajectories of the congruent trials. In the fourth experiment, I expected this congruency effect to be larger than the one extracted from the keyboard-RT.

Pilot Experiment 1

The aim of the first experiment was to test the effect of unconscious processing on motion trajectory. This was a pilot experiment where I developed and troubleshooted the apparatus, as well as explored meaningful parameters from the recorded trajectories.

Methods

Participants

Ten participants (eight females) between the ages of eighteen and thirty-five were recruited for the study (age: M = 24.2, SD = 2.57). All participants were right-handed, native Hebrew speakers who have normal vision or corrected-to-normal vision. Only participants declaring that they have no neurological, attentional, or mental disorders, and are not taking psychiatric medicines, were included. All participants in this and subsequent experiments signed a consent form and were explained that they could stop the experiment at any point if they wished to do so. They were reimbursed with course credit or cash payment. This experiment – and all others reported here – was approved by the Tel Aviv University ethics committee.

Stimuli

One hundred 5-letter words were used as primes and targets. All words were imageable nouns with a frequency of at least 10 per million (Frost & Plaut, 2005). One half described artificial products (e.g., radio, train) and the other natural items (e.g., fruit). Target words were written in typescript while prime words were written in handwriting font. Masks were composed of a semi-random combination of squares and diamonds whose line thickness is equal to the word's font size and which covers the central area of the screen where words can appear (approximately $2.5° \times 1°$). Forty words were used for the practice block and the remaining sixty were used in the test blocks.

Apparatus

The stimulus was displayed on a VPIXX monitor (VIEWPixx /3D Lite LCD display and data acquisition system, version 3.7.6287) using Matlab R2020b (*MATLAB*, 2020) and Psychtoolbox 3.0.18 (Brainard, 1997). The monitor was set to full brightness at a resolution of 1920 x 1080 and refresh rate of 100Hz with VPIXX's "Scanning backlight" feature turned on, which synchronizes the stimulus display to the screen's refresh rate. A Perspex cover was placed over the screen to protect it. The cover was spray painted with a light layer of transparent matte lacquer to avoid reflections. The participants sat approximately 60cm away from the screen and placed their index finger on a marked starting point located on the table 40cm away from the screen, in line with its center. The stimulus was displayed 24cm above the table and the classification answers were displayed on each side of it, 20cm apart (Figure 1). Participants wore a Velcro ring with a marker at the tip of their index finger. A touch was registered when the marker was 3cm away from the screen or closer. A system of 6 OptiTrack Flex 13 cameras by NaturalPoint, Inc. tracked the marker's location using Motive 2.3.0 software (*Motive*, 2021) at a sampling rate of 120Hz. The coordinates were broadcasted online to a NatNet client (*NatNet SDK*, 2021) and recorded with Matlab.

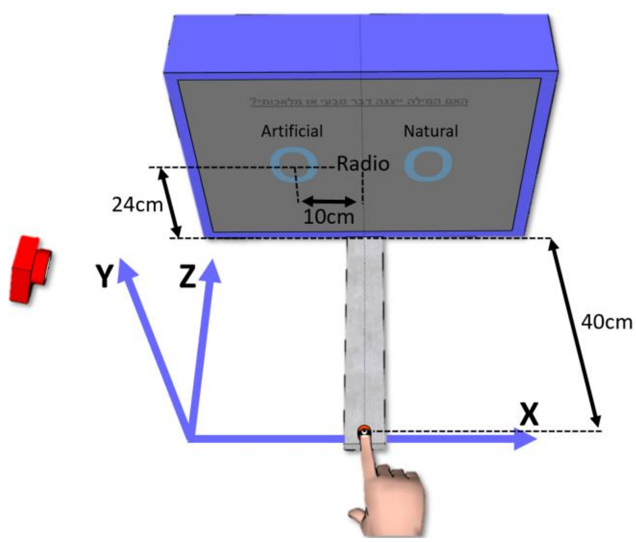


Figure 1. Setup. A participant placing his finger on the starting point which is located 40cm away from the screen. The target is positioned 24cm above the starting point and the answers are placed on each of its sides, 20cm apart. Z axis maps the path to and from the screen. X axis maps the left and right directions. Y axis maps the up and down directions.

Procedure

Each session included a practice block and twelve test blocks of forty trials each (i.e., 40 practice trials and 480 test trials). Breaks were given between blocks. Half the trials were congruent and half incongruent, and half the targets were natural and half artificial. Stimuli order in the experimental blocks was dictated by a list that was randomly sampled (without replacement) out of ten pre-composed lists of trial condition and stimulus. An additional practice list was used for all participants. In each list, the order of words was pseudorandom, with the following constraints: (a) Each word was equally frequent as a target at the congruent and incongruent conditions; (b) All words were used as targets the same number of times; (c) A target never repeated in the same block; (d) In the congruent condition the prime was identical to the target word; (e) In the incongruent condition, a prime which doesn't share letters in common locations with the target was selected from the alternative category (artificial/natural). For example, in the congruent condition, the word "phone" would be preceded by "PHONE", while in the incongruent condition it could be preceded by "GRASS". Each prime was further paired with a random distractor from the same category (artificial/natural) to be used in the prime recognition task. The distractor shared no letters in common locations with the prime, so seeing one letter only sufficed for correct discrimination.

The procedure closely followed the one used in Dehaene et al. (2001), yet in a motion tracking setup. Every trial consisted of a fixation cross (1000ms), a first mask (270ms), a second mask (30ms), a prime word (30ms), a third mask (30ms) and a target (500ms). Once the target was displayed, participants classified the target word as describing a natural / artificial item by reaching the side of the screen that contains the appropriate category (Figure 2**Error! Reference source not found.**). Responses had to be provided within a 1500ms time window from target presentation. Movement duration was defined as the time between target onset and the point when the finger was 3cm away from the screen or closer (on the Z axis). Responses slower than 1500ms were followed by "Move faster" feedback. After Classifying the targets, the participants were asked to recognize the prime as an objective measure of prime awareness. Participants were presented with two words – the prime and another word from the same category. Response was given in an identical fashion to the target classification task, within a 5 seconds response window. Then, a subjective measure of prime awareness was taken, using the Perceptual Awareness Scale (PAS; Sandberg & Overgaard, 2015). Participants used the keyboard numbers 1-4 to rate how well did they see the prime (1 – "Didn't see anything", 2 – "Saw something vaguely, but can't say what it is", 3 – "Saw part of the prime clearly", 4 – "Saw the whole prime clearly"). Finally, participants were asked to return their finger to the starting point.

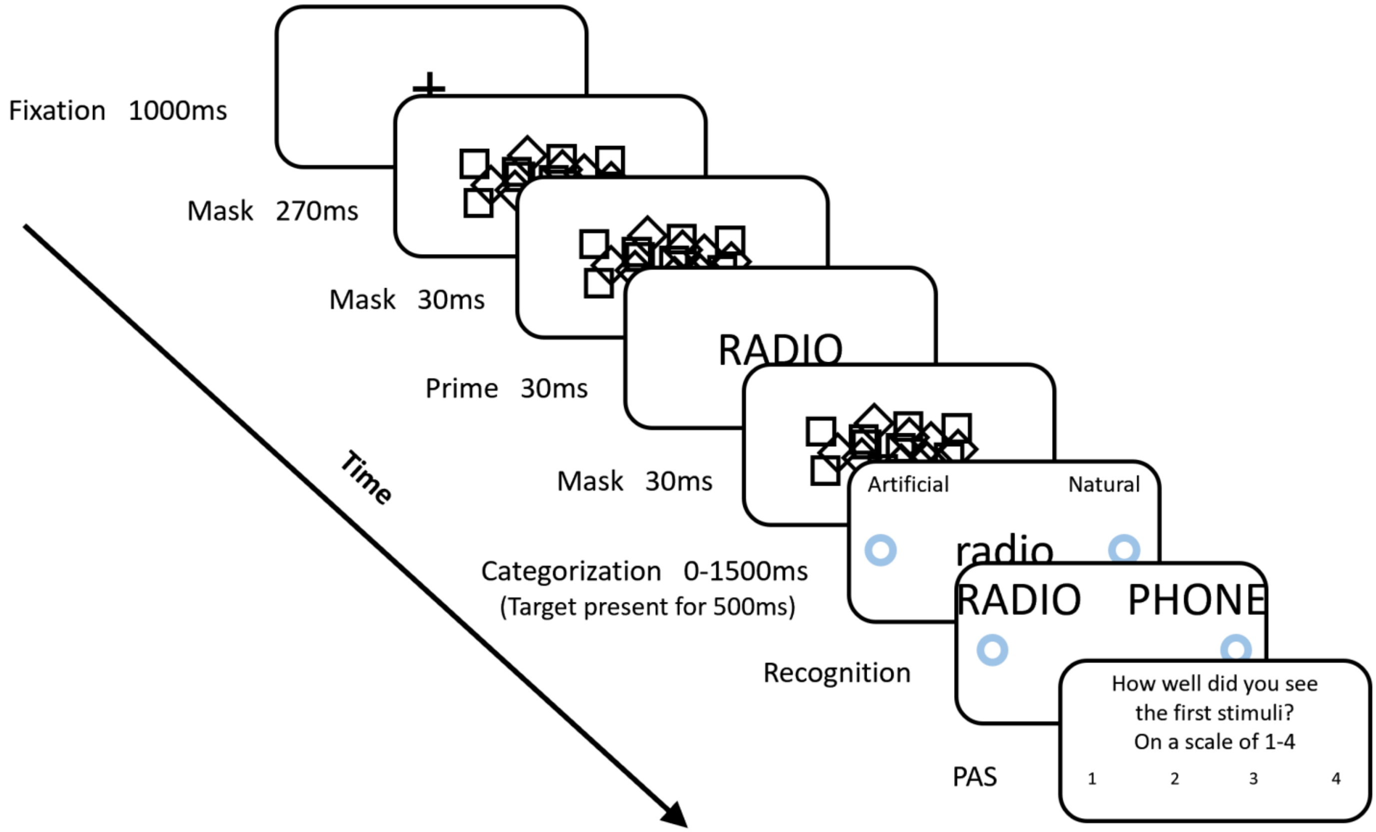


Figure 2. Stimuli presentation order in experiment 1. Each trial was composed of a fixation cross (1000ms), a first mask (270ms), a second mask (30ms), a prime word (30ms), a third mask (30ms), a classification task (0-1500ms, out of which the target was displayed for 500ms), a recognition task (0-5,000ms) and a PAS task (no time limit). The blue circles appearing on the screen are presented as markers for the participants to know where they should touch in order to make their response.

Trajectory preprocessing

The preprocessing procedures followed those described in Gallivan & Chapman (2014). Missing values were interpolated with the inpaint_nans function (D'Errico, 2022) to fill gaps in the trajectory, which was then filtered with a low pass butterworth filter (2^{nd} order with cutoff at 8Hz) to reduce noise. The axis' origin was set at the first sample of each trial. To locate reaching onset, a low pass butterworth filter (2^{nd} order with a 10Hz cutoff) was applied to the 3D velocity. *Reaching onset* was indicated by four consecutive samples having a velocity greater than 20mm/s and a total acceleration of at least 20mm/s^2. *Reaching offset* was determined as the point along the trajectory that is closest to the screen. The trajectories were normalized to the distance traveled along the axis perpendicular to the screen (Z axis). To do so, a B-spline of the 6th order with a roughness penalty $\lambda = 10^{-18}$ on the 4th derivative was fitted to each axis with a spline at every data point. The fitted function was used to produce a high-resolution representation of the trajectory (1000 samples) from which 200 points equally spaced along the traveled distance on the Z axis were extracted (e.g., if the participant moved 2cm forward and 1cm backward, the distance that was traveled was 3cm). These points represented the proportion of path traveled until each point.

Variables extraction

The congruency effect was estimated with five reaching parameters: (a) reach area, defined as the area confined between the average trajectory to the left side when the correct answer is on the left and the average trajectory to the right when the correct answer is on the right; (b) reaction time, defined as the time from stimulus presentation up to movement onset. Movement onset and movement offset were distinguished from reaching onset and offset. *Movement onset* was detected once the Euclidean distance from the starting point was greater than 2cm. *Movement offset* was recognized once the distance from the screen on the Z axis was shorter than 3cm; (c) movement duration, defined as the time from movement onset until the screen was reached; (d) changes of mind (COM), defined as the number of changes in implied goal along a single trial's trajectory. The implied goal was indicated by the side where the current tangent to the trajectory met the screen; (e) distance traveled, defined as the sum of Euclidean distances between the samples of a single trial.

Exclusion criteria

Trials in which either a technical malfunction occurred, or a problematic response was given, as well as trials that had a visibility rating that is higher than one, were excluded from the analysis. A technical malfunction alludes to trajectories that had less than 100ms of existing data or more than 100ms of missing data, or trials in which the stimuli duration was incorrect. Problematic responses include incorrect answers and trajectories that missed the target by more than 12cm, as well as reaching movements that were shorter – when measured along the z axis – than the distance between the starting point and the screen, minus a three-centimeter allowance that accounts for small variations in reaching onset. Finally, slow movements were disqualified if they were located more than 3 standard deviations (SD) from the average movement duration across the participant's correctly answered trials that did not have missing data.

Results

Prime visibility: overall, 71.94% of the trials were rated as visibility 1, 23.41% as visibility 2, 3.69% as visibility 3 and 0.95% as visibility 4. Because using identical primes and target words in the congruent condition biases the responses towards the target, I only analyzed the responses in the incongruent condition to estimate prime visibility. When participants rated the prime as invisible, they were not better than chance at recognizing it, $M = 50.64\%$, $SD = 3.41$, $t(9) = 0.59$, $p = 0.560$, 95% CI = [48.20, 53.09]. Thus, both the subjective and the objective measures confirm that masking was effective in rendering the stimuli invisible.

Congruency effect: All the comparisons between the congruent and incongruent conditions in all four experiments were corrected for multiple comparisons using the Tree-BH (Supplementary Figure 1) method suggested in Bogomolov et al. (2021). In addition, normality of the residuals was tested with a QQ-plot, and a permutation test (Kohl, 2019) was used to assess differences in variables that did not pass the normality test (for a list of such variables see Supplementary Figure 2). In Experiment 1, no differences were found between the congruent and incongruent conditions (Figure 3). However, small trends were observed, specifically in the reach area which was numerically smaller in the incongruent condition and reaction time which was numerically longer (Table 1).

Table 1. Results of Experiment 1

	Congruent	Incongruent				
	M (SD)	**M (SD)**	**t(9)**	**p**	**CI**	**d**
Reaching						
Reach area	2.80 (0.47)	2.70 (0.50)	2.16	0.169	0, 0.20	0.69
Traveled distance	40.88 (1.49)	41.06 (1.59)		0.694	-0.51, 0.17	0.30
Reaction time	433.96 (125.26)	441.88 (125.81)	2.07	0.169	-16.55, 0.71	0.66
Movement duration	558.15 (80.72)	557.91 (81.61)		0.896	-5.96, 5.60	0.02
COM	0.21 (0.06)	0.20 (0.08)	0.30	0.896	-0.03, 0.04	0.10

Note. t(df) = t-test score, only for variables whose residuals distributed normally. Degrees of freedom are in parenthesis; p = Tree-BH corrected p-value for multiple comparisons; CI = 95% confidence intervals; d = Cohen's d.

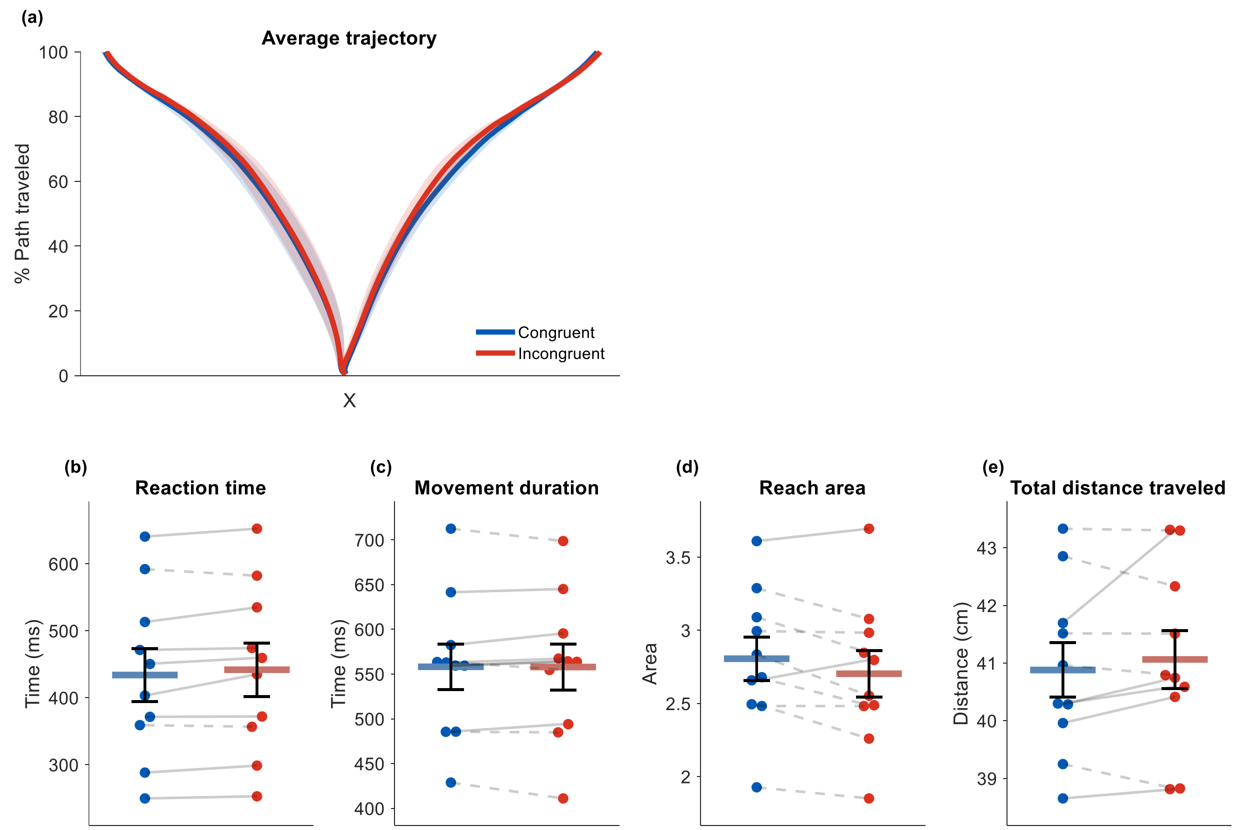


Figure 3. Results of Experiment 1. (a) Reaching trajectories in trials where a correct answer was given by choosing the left and right targets, averaged across all participants. Shaded areas are the standard error (SE). (b-e) Dots are single participant averages while the red/blue horizontal lines are the average of all participants. Black error bars symbol the SE. Full/dashed grey lines represent a numerical incline/decline (respectively) between the congruent and incongruent conditions.

Discussion

Experiment 1 was conducted to establish an experimental environment capable of capturing unconscious effects with motion tracking. In contrast to my expectations, a robust unconscious effect was not found in any of the motion tracking measures, although trends were found for some of them. As the trend was most prominent in the reach area variable, I reasoned that it might be the optimal variable for probing unconscious processing, and accordingly decided to focus on it in subsequent experiments. Interestingly, although the movement duration was similar in both conditions, there was a trend to longer reaction times in the incongruent condition.

Pilot Experiment 2

A possible explanation for the null results found in Experiment 1 might pertain to the relatively long time-window given for response. Under that condition, participants could have reached a decision even before initiating their movements. To illustrate, let us assume that decision was made using some form of evidence accumulation (Mattler & Palmer, 2012). In evidence accumulation models, the presentation of a stimulus is held to prompt an evidence accumulation process until a response that corresponds to the stimulus is chosen. Evidence builds up to a threshold, and once it is reached, a decision is made. If an opposing stimulus is presented before the threshold is reached, evidence starts to accumulate in the opposite direction, and the decision is delayed. Applied to Experiment 1, and to priming paradigms in general, in incongruent trials the prime and the target provide contradictory evidence, which delays the crossing of the threshold, and gives rise to longer response times in incongruent trials (Dehaene et al., 1998, 2001; Dell'Acqua & Grainger, 1999). However, in my experiment the movement duration was identical for both conditions. On the other hand, reaction times (i.e., time it takes to initiate the movement to begin with) showed a trend towards longer responses in incongruent trials. This raises the possibility that the decision was actually made before the movement has started. Thus, participants initiated a reaching movement directly at their final answer without revealing any of the processes that lead to choosing it. As a result, the congruency effect was not expressed in the movement itself.

Therefore, in experiment 2, the time window for response was restricted, and movement duration was decreased. Since quicker responses were required, a second training block was added to make sure participants learn to respond within the required time window. I expected the movements to reflect a greater unconscious effect than in Experiment 1 considering that participants will not have enough time to make a decision before starting their movement.

Methods

Participants

Nine participants (7 females) were recruited for the study (age: M=23.66, SD=2.44) using the same recruitment procedure as in experiment 1. Five additional participants were disqualified from the analysis, as they met two of the following predefined exclusion criteria: (a) having less than 25 valid trials in each condition (N=3); and (b) showing performance lower than 70% in the main classification task (N=2; determined using a binomial test). Another participant was excluded because the experiment crashed during her session.

Stimuli, Apparatus and Procedure

The methods were identical to those used in Experiment 1, besides the following differences: first, the starting point was now 35cm away from the screen and the size of the blue circle beneath each target was slightly increased so that hitting it will be easier. Second, here the participants completed an initial practice block that did not include a prime. The order of trials in this block was drawn from an additional list of trial condition and stimulus. Third, timing was adjusted so that movements had to start before 330ms had passed and last no longer than 430ms. Movement started when the finger was 2cm away from the starting point (Euclidean distance) and ended when it was 3cm away from the screen (on the Z axis). Late initiations and long durations were followed by a "Too late" and "Too slow" feedbacks, respectively. Recognition responses were given within a 7 second response window.

Exclusion criteria

Additional restrictions were placed on the participants' reaching movements, limiting their reaction time and movement duration. Movements that started less than 100ms or more than 320ms after target display were excluded. In addition, movements that lasted more than 420ms were excluded if they were located more than 3 SD from the participant's average movement duration among correct trials that were not too short, had no missing data and were completed in time (i.e., started between 100ms and 320ms after target display and lasted no longer than 420ms). *Valid trials* were those that were not excluded due to any exclusion criteria.

Results

Prime visibility: in total, visibility ratings of 1 were given in 81.63% of the trials, visibility ratings of 2 in 16.07% of the trials, visibility ratings of 3 in 1.83% of the trials and visibility ratings of 4 in 0.46% of the trials. Subjectively invisible stimulus was recognized at chance level, M = 50.26%, SD = 2.57, t(8) = 0.30, p = 0.770, 95% CI = [48.27, 52.24]. Again, this confirms the efficiency of my masking procedure (as will be the case for the two subsequent experiments, see below).

Congruency effect: Similarly to Experiment 1, a congruency effect was not reflected in any of the dependent variables (Figure 4; Table 2).

Table 2. Results of Experiment 2

	Congruent	Incongruent				
	M (SD)	**M (SD)**	**t(8)**	**p**	**CI**	**d**
Reaching						
Reach area	1.50 (0.28)	1.39 (0.64)		0.699	-0.14, 0.36	0.23
Traveled distance	37.20 (1.09)	37.67 (1.17)	1	0.342	-1.54, 0.60	0.34
Reaction time	140.44 (34.23)	144.27 (33.21)		0.273	-9.62, 1.93	0.40
Movement duration	416.56 (60.57)	423.96 (45.40)		0.316	-17.63, 2.74	0.40
COM	0.26 (0.08)	0.27 (0.12)		0.781	-0.08, 0.05	0.13

Note. t(df) = t-test score, only for variables whose residuals distributed normally. Degrees of freedom are in parenthesis; p = Tree-BH corrected p-value for multiple comparisons; CI = 95% confidence intervals; d = Cohen's d.

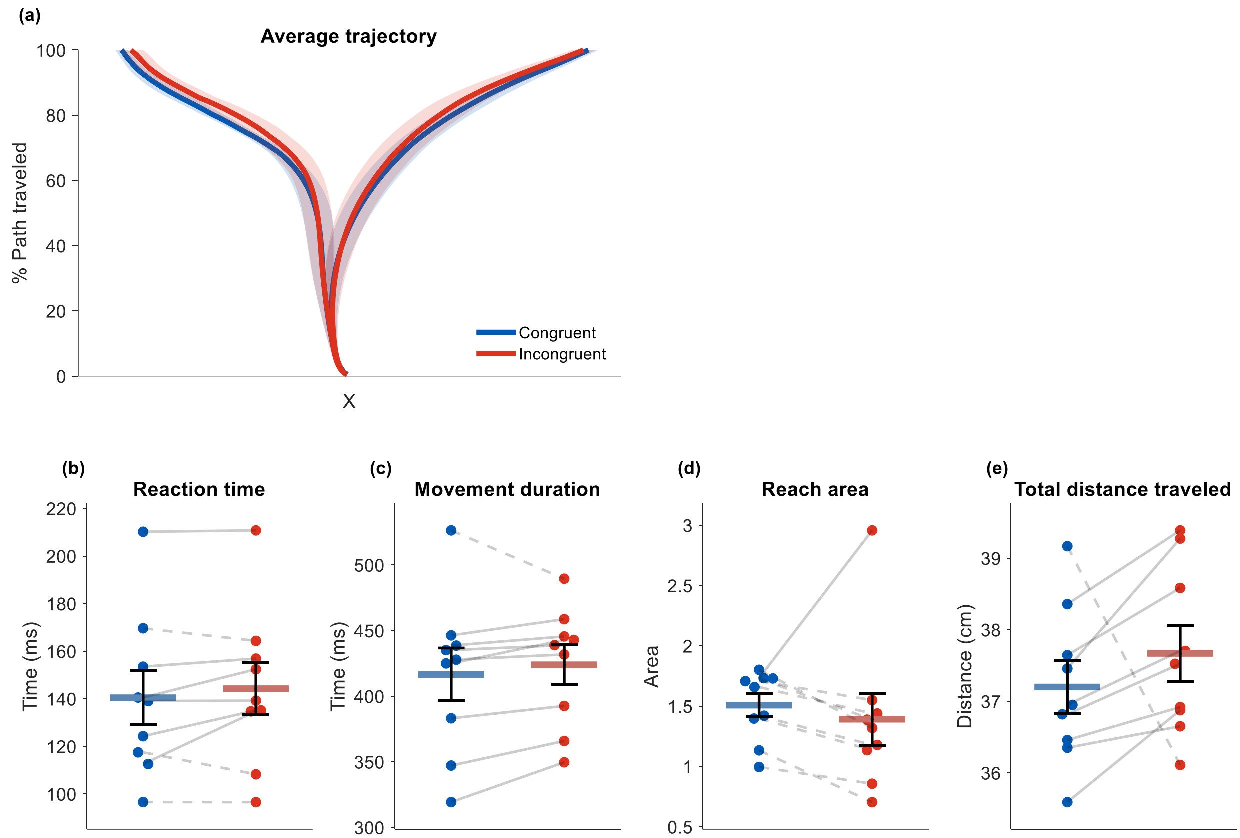


Figure 4. Results of Experiment 2. (a) Reaching trajectories in trials where a correct answer was given. Shaded areas are the SE. (b-e) results of the different movement variables, with the same annotations as in Figure 3.

Discussion

In Experiment 2 the participants' ability to reach their final decision before initiating their movement was intentionally limited by the shortened reaction time. Consequently, I expected the decision-making processes to occur during the movement and manifest in differences in the trajectory between the congruent and incongruent trials. Yet this expectation was not borne out by the data, as null results were observed for all the dependent variables. An examination of the reach area distribution shows that a single participant had a strong opposite trend to the rest of the sample, which might explain why a significant difference between the means could not be found (Figure 4, (d)). Indeed, a post-hoc analysis revealed that when this participant is excluded an effect is found in the reach area variable ($p < 0.001$). Expectedly, reducing the allowed reaction time in this experiment resulted in a large average number of excluded trials (M = 214.11, SD = 71.12) which might also explain the difficulty to find an effect, as this also reduces the signal to noise ratio.

Pilot Experiment 3

Given the large proportion of excluded trials, in Experiment 3 the practice session was substantially prolonged into a full session conducted a day before the test session. I anticipated that if participants learn to respond more quickly, there will be less incorrect answers and too-slow timing responses, leading to less exclusions. This in turn was expected to increase the signal-to-noise ratio, and allow the congruency effect to be found.

Methods

Participants

Seven participants (5 females) were recruited for the study (age: M = 24.42, SD = 3.20) in a recruitment procedure identical to experiment 1. Four additional participants were excluded since they did not arrive to the second day of the experiment. One more participant was excluded because he had less than 25 valid trials in each condition, and five other participants were excluded since they achieved significantly less than 70% correct answers in the classification task according to a binomial test.

Stimuli, Apparatus and Procedure

The experimental methods were identical to those used in Experiment 2, besides the following changes: first, the maximal movement onset and movement duration were reduced by 10ms to 320ms and 420ms respectively to make sure they do not exceed those used in Gallivan & Chapman (2014). Recognition of movement onset and offset was also adjusted to improve their consistency across trials, so movement started when the finger was 1cm away from the starting point (Euclidean distance) and ended when it was 1.5cm away from the screen (on the Z axis). Second, "Too early" feedback was given if the participant responded less then 100ms after target presentation. The purpose of the "Too early" feedback was to prevent predictive responses, which are planned before the stimulus is displayed and are therefore less affected by it. Third, and most importantly, a longer practice session was run on a separate day before the main experimental session. It included six practice blocks, where a different set of 60 4-letter words was used as primes and targets. All words followed the same criteria as in the previous experiments. These stimuli were drawn from a set of ten pseudo random lists of condition and stimulus order, which followed the same constraints as the test session lists.

Results

Prime visibility: PAS visibility ratings of 1/2/3/4 were given in 76.29%/20.08%/2.85%/0.76% of the trials, respectively. Chance level recognition was observed for stimuli that was reported as invisible, $M = 47.46\%$, $SD = 3.45$, $t(6) = -1.94$, $p = 0.100$, 95% CI = [44.26, 50.65].

Congruency effect: Contrary to Experiment 2, a prominent difference was found in reach area, which was smaller in the incongruent condition than in the congruent one (Figure 5). However this difference, as well as the difference in the other dependent variables (Table 3), did not survive the multiple comparisons correction.

As opposed to my expectation, no difference was found between the response time in the first block of the first and the second days ($M_1 = 535.97$, $SD_1 = 63.18$, $M_2 = 455.76$, $SD_2 = 97.56$, $t(6) = 1.86$, $p = 0.111$, 95% CI [-24.94, 185.36]). Furthermore, the average number of valid trials exhibited an unexpected decreasing trend between Experiment 2 and Experiment 3 ($M_2 = 234.44$, $SD_2 = 84.66$, $M_3 = 162.57$, $SD_3 = 63.23$, $t(14) = -1.87$, $p = 0.082$, 95% CI [-154.25, 10.51]; For an elaborative description of the excluded trials see Supplementary Table 1).

Table 3. Results of Experiment 3

	Congruent	**Incongruent**				
	M (SD)	**M (SD)**	**t(6)**	**p**	**CI**	**d**
Reaching						
Reach area	2 (0.30)	1.73 (0.25)	3.02	0.023	0.05, 0.48	1.14
Traveled distance	38.27 (1.25)	39.23 (1.74)	3.69	0.010	-1.59, -0.32	1.40
Reaction time	164.46 (26.10)	175.93 (15.40)	2.22	0.067	-24.08, 1.12	0.84
Movement duration	391.95 (32.91)	403.35 (25.40)	2.41	0.051	-22.92, 0.13	0.91
COM	0.20 (0.13)	0.20 (0.15)	0.05	0.959	-0.10, 0.10	0.02

Note. t(df) = t-test score. Degrees of freedom are in parenthesis; p = Tree-BH corrected p-value for multiple comparisons; CI = 95% confidence intervals; d = Cohen's d.

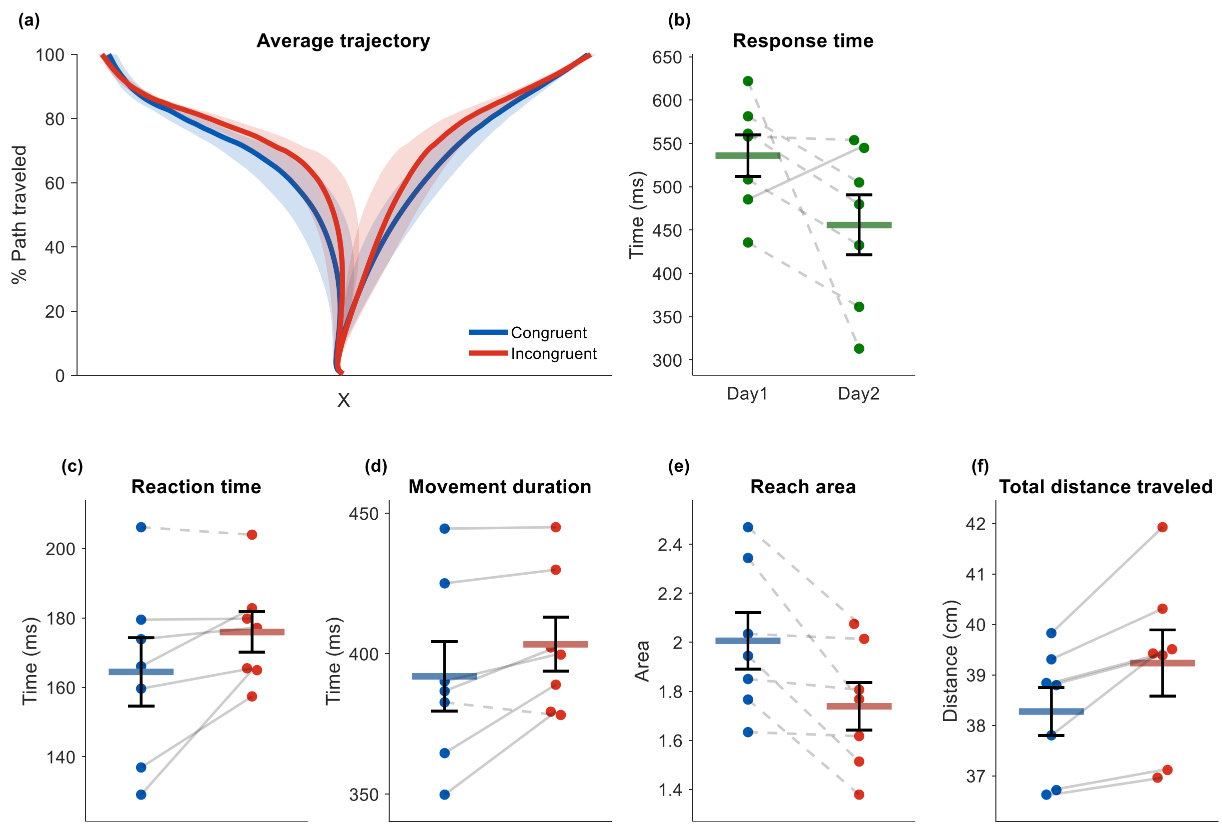


Figure 5. Results of Experiment 3. (a) Reaching trajectories in trials where a correct answer was given by choosing the left and right targets, averaged across all participants. Shaded areas are the SE. (b) Response time in the first block of the first and second days. (b-f) Dots are single participant averages while the colored horizontal lines are the average of all participants. Black error bars symbol the SE. Full/dashed grey lines represent a numerical incline/decline (respectively) between the congruent and incongruent conditions.

Discussion

Experiment 3 incorporated a prolonged practice session in order to decrease the number of excluded trials and improve the probability of detecting the unconscious effects. Notably, none of the comparisons passed the multiple comparisons correction. However, interesting trends did imply a congruency effect which manifested as a bias in the trajectories towards the incorrect answer in the incongruent trials. This bias was expressed in a decreasing trend in the reach area for incongruent trials. The results are in-line with previous papers that found a larger Area Under the Curve (AUC) for incongruent as opposed to congruent trials (Almeida et al., 2014; Xiao & Yamauchi, 2017).

Surprisingly, the additional practice day in Experiment 3 did not significantly reduce the participants' response time or proportion of excluded trials, and was therefore forgone in the next experiment.

Experiment 4

Experiment 4 was preregistered (https://osf.io/8dsvp), aimed at examining whether motion tracking is preferable over keyboard responses when studying unconscious processing. Accordingly, it included both motion tracking and keyboard responses sessions, allowing me to compare the sensitivity of both measures on an identical task. My approach followed the one by Xiao et al. (2015), but replaced the mouse response with a more intuitive and less effortful reaching response which does not constrain free movement (Desmurget et al., 1997; Palluel-Germain et al., 2004). Additionally, I improved the validity of the unconscious results by applying a rigorous awareness detection procedure that includes both an objective awareness measure (prime 2-forced-choice recognition) and a subjective trial by trial awareness measure (PAS). As opposed to Xiao et al. (2015) which used an awareness measure on a separate block, awareness in my experiment was estimated in the trials of the main task. Since Experiment 3 have shown that additional practice does not improve the number of valid trials, a separate training day was not included in Experiment 4, and only one practice block was used for each session. To prevent fatigue, each session included half the number of trials (after testing that the effect found in Experiment 3 is found also when half the trials are used). In accordance with previous findings (Xiao et al., 2015; but see Dehaene et al., 2001, were a large effect was found using a keyboard) I expected that the effect found in the motion tracking session (namely, the reach area variable) would produce a larger congruency effect than the effect in the keyboard session (RT variable).

Methods

Participants

The recruitment procedure and criteria were identical to those of Experiment 1. Thirty participants (17 females) were recruited (age: M = 26.9, SD = 3.66) and additional 15 participants were excluded. Five of them were excluded because they had significantly less than 70% correct answers in the target classification task according to a binomial test. Seven participants were excluded since they had less than 25 valid trials in each condition. Three more participants were excluded due to technical issues: one since a reflective object she wore interfered with the motion tracking system's recordings, another participant since the program crashed in the middle of her experiment, and one more quit before completing the experiment. The sample size was determined following a power analysis, calculated on the average of the effects in Experiments 2 and 3, when using only half of the trials in each experiment. The average effect size was 0.88 (Cohen's d_z; see Lakens, 2013). I estimated the keyboard task's effect size to be around 30% smaller (Cohen's d_z = 0.61), in line with my hypothesis for a smaller RT effect, and in accordance with a previous study (Xiao et al., 2015, d=0.65, though see Dehaene et al., 2001, where the effect size was 0.8). To find such effect with a power = 95% and α = 0.05, a sample of 30 participants was needed, based on G*Power (Faul et al., 2007, 2009).

Stimuli, Apparatus and Procedure

The methods were identical to those used in Experiment 3, besides the following changes: first, the separate practice day was omitted and instead two main sessions were conducted on the same day, one for keyboard response and the other for motion tracking. Each included a practice block and six test blocks (i.e., 40 practice trials and 240 test trials). They were run consecutively, with the order counterbalanced between participants. Stimuli order in the experimental blocks was dictated by a list that was randomly sampled (without replacement) out of twenty pre-composed lists of trial condition and stimulus. Reaching responses were bound to the same movement onset and duration constraints as in Experiment 3. However, here to make sure participants touch the screen, movement ended when the finger was 0.7cm away from the screen (on the Z axis), and to avoid interrupting the participant's movement, the "Too slow" feedback was given after the movement was completed. In the keyboard task participants pressed "E"/"Y" keys with the left/right hand to select the left/right side accordingly. Response had to be given within a time window of 100-740ms from target display, otherwise "Too Early"/ "Too Late" feedback was given. Response in the prime recognition task was given in an identical fashion to the target classification task, within a seven second response window.

Exclusion criteria

The exclusion criteria in the reaching session were identical to those used in experiments 2 and 3. Additional exclusion criteria were used in the keyboard session, where trials were excluded if no response was given or if it was given less than 100ms or more than 740ms after target display.

Results

Prime visibility: In the reaching session, 94.41% of the trials were given a visibility rating of 1, 4.79% a visibility rating of 2, 0.63% a visibility rating of 3 and 0.15% a visibility rating of 4, while in the keyboard session 92.12% of them were given a visibility rating of 1, 7.04% a visibility rating of 2, 0.70% a visibility rating of 3 and 0.12% a visibility rating of 4. Objective recognition performance for the subjectively invisible stimuli was at chance level, both in the reaching session (M = 50.82%, SD = 4.32, t(29) = 1.03, p = 0.31, 95% CI = [49.20, 52.43]) and the keyboard session (M = 50.22%, SD = 4.55, t(29) = 0.26, p = 0.790, 95% CI = [48.52, 51.92]). Thus, both awareness measures indicate that the subjectively invisible stimuli were not consciously perceived.

Congruency effect: A congruency effect was found in both measures, as was evident by the smaller reach area and slower keyboard-RT in the incongruent condition (Table 4). Comparison of the effect sizes revealed that the keyboard-RT effect (Cohen's d = -1.17) was larger than the reach area effect (Cohen's d = 0.69). A bias towards the incorrect answer in incongruent trials was evident in the trajectory from 175.66ms to 390.88ms post target onset (24-94% path) as was found using a permutation and clustering procedure (Figure 6, (a)). The bias resulted in an extended traveled distance and a prolonged movement duration in incongruent trials. In contrast, reaction time and the number of changes of mind in the reaching session did not differ between the conditions.

As predicted by Experiment 2 and Experiment 3, the number of excluded trials in the reaching task was high and in fact exceeded that of the keyboard task (M_{reach} = 128.76, SD_{reach} = 35.52, $M_{keyboard}$ = 50.2, $SD_{keyboard}$ = 14.47, t(29) = 12.70, p < 0.001, 95% CI [65.91, 91.21], Cohen's d_z = 2.31). Further inspection however revealed this was true for late responses and early responses but not for incorrect answers which were less common in the reaching task (for an elaborative description of the excluded trials see Supplementary Table 2).

Table 4. Results of Experiment 4

	Congruent	Incongruent				
	M (SD)	**M (SD)**	**t(29)**	**p**	**CI**	**d**
Reaching						
Reach area	2.09 (0.51)	1.74 (0.49)		0.001*	0.16, 0.52	0.69
Traveled distance	38.20 (1.44)	39.09 (1.67)		<0.001*	-1.25, -0.56	0.95
Reaction time	171.29 (22.42)	173.06 (23.95)	1.01	0.318	-5.31, 1.79	0.19
Movement duration	415.88 (29.76)	429 (28.32)	6.40	<0.001*	-17.32, -8.93	1.17
COM	0.24 (0.12)	0.22 (0.11)	1.06	0.318	-0.02, 0.06	0.19
Keyboard						
Response Time	525.53 (35.76)	545.46 (32.87)	6.42	<0.001*	-26.27, -13.58	1.17

Note. t(df) = t-test score, only for variables whose residuals distributed normally. Degrees of freedom are in parenthesis; p = Tree-BH corrected p-value for multiple comparisons; CI = 95% confidence intervals; d = Cohen's d.

* p < p value for $\alpha = 0.05$ after adjustment according to Tree-BH method.

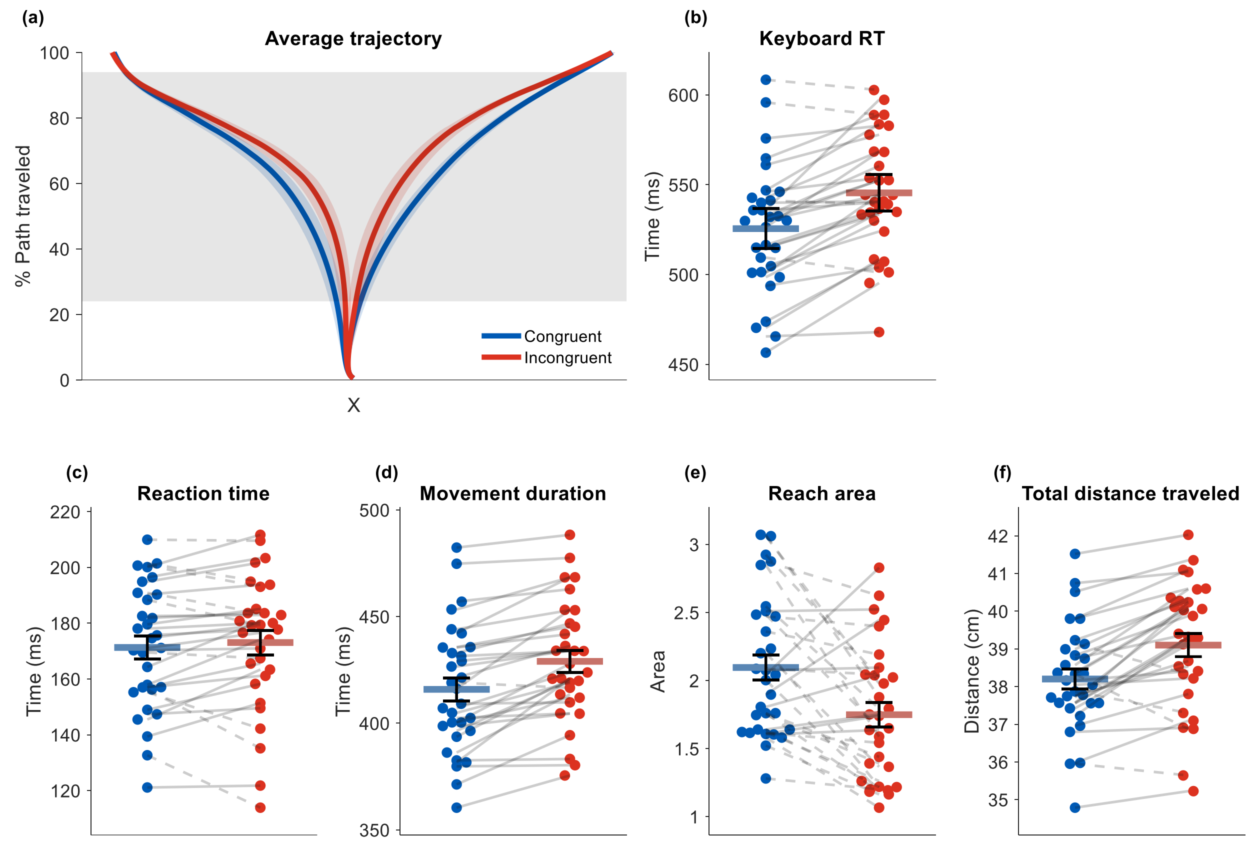


Figure 6. Results of Experiment 4. (a) Reaching trajectories in trials where a correct answer was given by choosing the left and right targets, averaged across all participants. Shaded areas are the SE. Grey shade marks where the difference between the trajectories was found to be significant according to a permutation and clustering procedure. (b-f) Dots are single participant averages while the red/blue horizontal lines are the average of all participants. Black error bars symbol the SE. Full/dashed grey lines represent a numerical incline/decline (respectively) between the congruent and incongruent conditions.

Discussion

Experiment 4 compared the effect of unconscious processing as measured by motion tracking and keyboard presses. Despite previous criticisms about the robustness and reliability of evidence (e.g., Damian, 2001; Peters & Lau, 2015) a large congruency effect was found using both measures. In the reaching session, movements were clearly biased towards the incorrect answer when primed by an incongruent word, as was evident by the centrally oriented reaching trajectories which produced a smaller reach area, longer traveled distance and longer movement duration. The difference between congruent and incongruent trajectories was significant approximately around 175.66ms to 390.88ms (24-94% of the path) post target onset showing that the prime exerts its effect almost throughout the entire movement (note however that this analysis should not be taken as evidence for the exact latency/offset of the effect; see Sassenhagen & Draschkow, 2019). However, contrary to my hypothesis, the effect size found for the reach area variable was smaller than that found with the keyboard-RT, although the reaching movement duration measure yielded comparable effects to the keyboard-RT. Possible explanations are discussed in the general discussion below.

General Discussion

One of the key driving forces behind the long-lasting debate about the extent of unconscious processing (Hassin, 2013; Hesselmann & Moors, 2015; Michel, 2019; Peters et al., 2017) pertains to the weak, and often small effect sizes that are usually found in the field (Greenwald et al., 1996; Van den Bussche et al., 2009). In this thesis, I set out to examine if motion tracking could solve this problem, by providing more sensitive measures that could potentially yield stronger effects (Xiao et al., 2015). To do so, I used a variant of the classical word repetition priming paradigm previously used by Dehaene et al. (2001), which allowed for continuous motion tracking while participants make reaching responses to classify a visible target word preceded by an invisible prime.

In Experiment 1, participants were presented with a subliminal prime, which was followed by a supraliminal target word, on which they performed a semantic judgment (i.e., determine whether the word described a natural item or a man-made artifact). Analysis of the results revealed a hint for unconscious processing in the reach area variable, which was numerically smaller for incongruent trials. Yet this trend was not significant, possibly since this experiment allowed for relatively slow responses. With such a long response window, subjects could have finalized the evidence accumulation processes and reached a decision (Mattler & Palmer, 2012) even before the movement was initiated. In this case, congruency effects are less likely to be revealed when movement is tracked. Supportive evidence for this interpretation can be found in the relatively long reaction times, but not movement durations, in incongruent trials (though again, no effects were significant in this experiment).

To circumvent this problem, the response window in Experiment 2 was reduced and limitations were placed on movement onset time and movement duration. Unfortunately, the strict timing constraints resulted in many excluded trials which increased the measured noise. A lower signal to noise ratio (SNR) together with a single participant with an extreme opposite effect to the rest of the sample, seemed to interfere with the congruency effect.

Experiment 3 was then conducted with an additional training day, to improve the participants' response speed and increase the number of valid trials. The expected congruency effect was now marginally found for the reach area variable. However, the additional training day did not increase the number of valid trials, and was therefore omitted in Experiment 4.

Finally, the preregistered Experiment 4 examined if motion tracking is superior to keyboard-RT when probing unconscious processing. In line with my predictions, both of which yielded robust effects. This result goes beyond previous studies, as the current design included stringent awareness measures, with trial by trial subjective and objective measures, mitigating previous criticisms attributing unconscious effects to residual undetected awareness (Merikle, 1992; Peters & Lau, 2015; Zerweck et al., 2021). Similarly, the unconscious effect could not result from regression to the mean of the awareness measurement (Shanks, 2017), since no participants were excluded for seeing the prime. To conclude, this experiment provides strong evidence for an unconscious word repetition effect, in line with previous studies reporting similar effects (yet with somewhat less strict awareness measures; Dehaene et al., 2001; Luo et al., 2004).

Importantly, this experiment demonstrated how motion tracking can be beneficial to the study of unconscious processes. Unlike keyboard responses, which are one dimensional and mark the outcome of the decision process, the reaching measure allows tracking the decision as it unfolds (Dotan et al., 2019; Freeman et al., 2011), including changes of mind and online corrections of response (Resulaj et al., 2009; Song & Nakayama, 2009). This type of behavior is particularly interesting in priming experiments because it might reflect a strong conflict between the prime and the target. Additionally, since participants can regret and self-correct during the trial, the number of incorrect responses (which are excluded from analysis) is reduced, as was indeed the case in the motion tracking session compared with the keyboard session in Experiment 4 (though notably, there more trials were excluded due to early or late responses).

Contrary to my hypothesis, the effect size in the keyboard condition was comparable to that found for the movement duration variable, and numerically larger than the effect found for the reach area measure. This result contrasts with the finding of Xiao et al. (2015), which suggested an advantage for mouse tracking over keyboard responses. One possible explanation for this discrepancy might stem from the different form of movement tracking; while I used a camerabased motion tracking for reaching movements, Xiao and colleagues have used mouse tracking, which might be more sensitive than reaching responses. However, reaching is held to be more intuitive than mouse pointing, which places less constraints on movements (Desmurget et al., 1997; Palluel-Germain et al., 2004) and accordingly is expected to be more sensitive to subtle effects. Indeed, previous findings showed that reaching responds faster and with greater curvatures to changes of mind than mouse tracking (Moher & Song, 2019).

Another difference between the current study and Xiao et al. (2015) pertains to the dependent variable. While I used the reach area measure, which is calculated on the average trajectories with a single value per participant, Xiao et al. used AUC which is computed separately for each trial. The latter accordingly includes more information on the variance that is lost when averaging trajectories over trials. However, a post hoc analysis using the AUC measure on my data reveled similar effect size to that produced by the reach area measure. Thus, this difference in analysis approaches cannot explain the differential results.

A more critical difference between the studies pertains to the awareness measures in the two studies. Xiao et al. (2015) assessed the contribution of awareness by examining the correlation between the objective visibility of the prime and the size of the congruency effect. This type of analysis has been shown to inflate unconscious effects, since the correlation measurement is limited by the reliability of either of the variables (Malejka et al., 2021). Furthermore, visual examination of the reported d' in that work reveals that the masking procedure was actually ineffective in rendering the prime completely invisible (as for most participants, d’ was higher than 0), allowing it to be consciously processed. Thus, it seems plausible that the reported effect is more driven by consciously processed primes, which might affect movements to a larger extent than unconscious ones, and that could account for the large effect found by Xiao and colleagues.

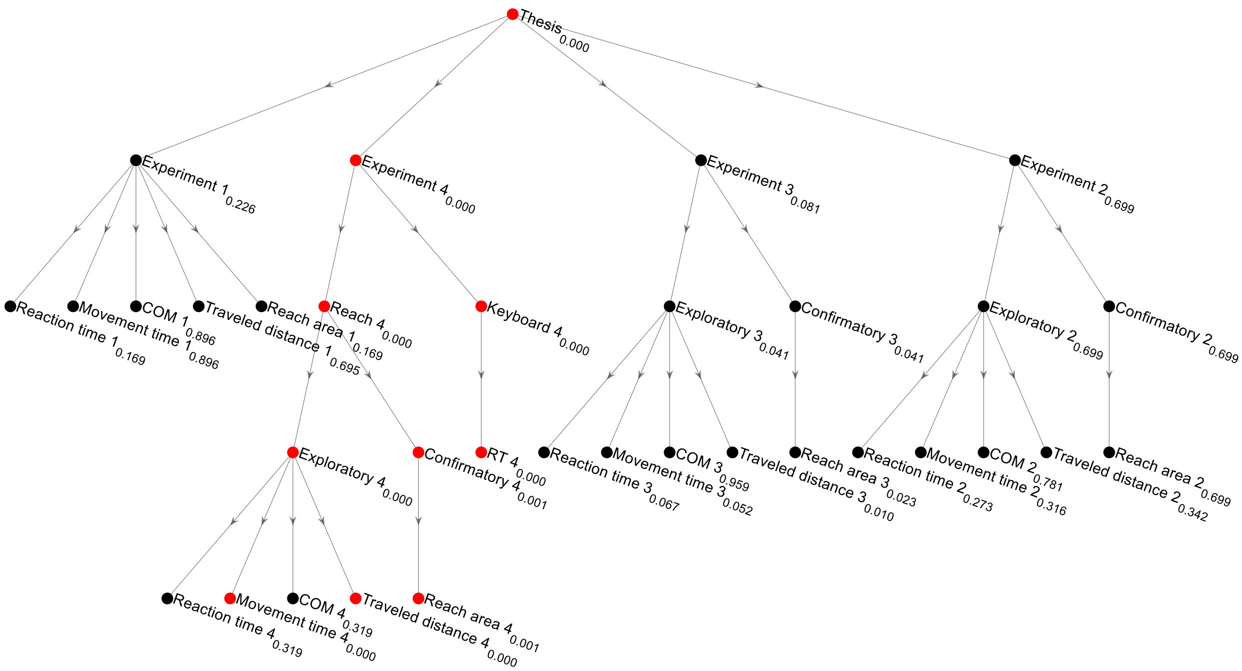
Finally, the discrepancy between the studies could also be accidental. It is possible that the one set of reported results is erroneous, which calls for further studies to examine the relation between reaching and keyboard responses. One way by which such studies could go beyond the current work would be to use a dynamic starting condition, in which the stimuli are presented only after the movement was initiated. This paradigm has been shown to increase the movement consistency and curvature and decrease the amount of noise (Scherbaum & Kieslich, 2018). Moreover, it will decrease the number of excluded trials, as no trials will be excluded due to early or late responses. This could potentially increase the signal to noise ratio in the reaching task and allow reaching to unravel a larger congruency effect.

Assuming the results obtained here are genuine, one could go beyond the discrepancy between them and those reported by Xiao et al. (2015), and ask how can we explain the current findings. That is, why was the expected pattern of a stronger effect for movement tracking not found. One possible explanation might stem from the larger amount of noise that was observed in the reaching measure. Specifically, reaching requires planning a trajectory towards a target, which makes it more complex than a simple keypress. The more complex a process is, the more room there is for error and variability when executing it (Nembhard & Osothsilp, 2002). This might obscure the congruency effect and make it harder to find in a complex reaching movement compared to a keypress. This notion is supported by the larger relative standard deviation (Everitt & Skrondal, 2010) observed in the reaching area (SD = 1.45) compared to the keyboard RT (SD = 0.85). In addition, the SNR was further decreased in the reaching session due to the higher number of excluded trials.

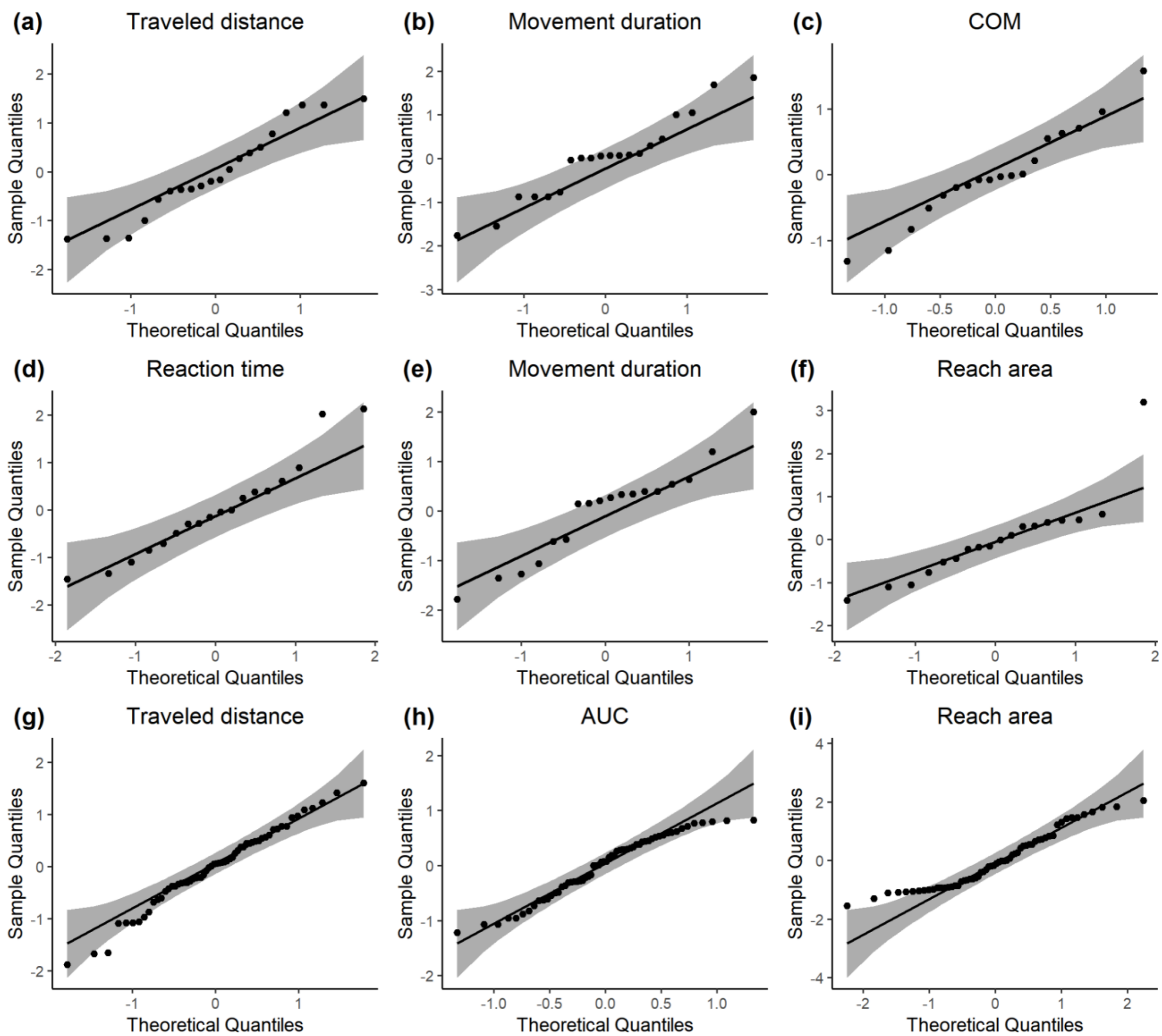
Another alternative explanation for the results relies on the short-lived nature of unconscious effects (Greenwald et al., 1996). As reaching responses are a relatively long ongoing procedure, they might be less affected by short-lived effects. However, this interpretation does not align with the cluster-based permutation results which show that the primes exerted their effects almost throughout the entire movement. Thus, it seems like the lower SNR is a more plausible explanation for the results.

To conclude, although no advantage in effect size was found for motion tracking, this study does suggest that it might be a fruitful venue for future research. First, the effects are comparable to those found when using a keyboard response measure of unconscious processing. Second, it provides rich data and online sensitivity that is not possible with a keyboard measure. This opens the gate to delving into the temporal aspects of unconscious effects on behavior. Thus, when taken together, these results should encourage researchers to further explore the features and potential in movement tracking as a tool for studying unconscious processes. New analyses and parameters should be devised and extracted from the trajectory data and could potentially expand our knowledge of processes taking place without consciousness.

Supplementary materials



Supplementary Figure 1. Hierarchy of the tree used in the Tree-BH method to correct for multiple comparisons. Nodes are statistical tests and their corrected p-values appear next to each test's name. Significant statistical tests that passed the adjusted alpha are marked in red.



Supplementary Figure 2. QQ-plots for the dependent variables that violated the normality assumption. (a-b) Experiment 1. (c-f) Experiment 2. (g-i) Experiment 4.

Supplementary Table 1. Comparison of the number of excluded trials between Experiment 3 and Experiment 2

	Experiment 2	**Experiment 3**			
	M (SD)	**M (SD)**	**t(14)**	**p**	**CI**
Short trajectories	14.55 (17.59)	70.28 (42.75)	3.56	0.003*	22.23, 89.22
Early responses	36.77 (40.96)	68 (65.20)	1.17	0.259	-25.77, 88.22
Late responses	58.88 (21.60)	54.57 (28.37)	0.34	0.734	-31.05, 22.41
Slow movements	9.66 (18.06)	0.57 (0.78)	1.32	0.207	-23.86, 5.67
Incorrect answers	72.11 (21.22)	49 (29.68)	1.82	0.090	-50.34, 4.12

Note. t(df) = t-test score, degrees of freedom are in parenthesis; p = p-value; CI = 95% confidence intervals.
* $p < 0.05$.

Supplementary Table 2. Comparison of the number of excluded trials in Experiment 4 between the reaching session and the keyboard session

	Reaching	**Keyboard**			
	M (SD)	**M (SD)**	**t(29)**	**p**	**CI**
Early responses	23.26 (19.79)	0 (0)	6.43	<0.001	15.87, 30.65
Late responses	32.06 (19.24)	14.06 (10.33)	4.71	<0.001	10.19, 25.80
Incorrect answers	21.90 (12.33)	36.13 (15.29)	6.31	<0.001	-18.84, -9.62

Note. t(df) = t-test score, degrees of freedom are in parenthesis; p = p-value; CI = 95% confidence intervals.

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תקציר

על אף היותם בלתי נראים עבורנו, גירויים לא מודעים הוכחו בעבר כמסוגלים להשפיע על ההתנהגות שלנו. למרות זאת, תחום המחקר של עיבוד לא מודע שופע בממצאים סותרים אשר מעוררים מחלוקות לגבי היקפו, ובאופן ספציפי לגבי עיבוד סמנטי. את המחלוקות הללו ניתן להסביר על ידי מגבלות מתודולוגיות אשר מאפיינות חלק מהמחקרים בתחום. מגבלה אחת, אשר נחקרת בתזה הנוכחית, היא הערכת חסר של עיבוד לא מודע הנובעת משימוש במדדים שאינם רגישים מספיק לאפקט הלא מודע. המדד הנפוץ ביותר לבחינה של אפקטים לא מודעים הינו זמן התגובה של תשובות הניתנות באמצעות מקלדת. אולם אמצעי זה בדרך כלל מפיק אפקטים קטנים מאוד ומספק מידע רק לגבי התשובה הסופית ולא לגבי ההליכים שהובילו אליה. פתרון אפשרי לשתי הבעיות הללו הוא שימוש באמצעים למעקב אחר תנועה, אשר הפכו לכלי נפוץ לחשיפת הליכים קוגניטיביים.

אך האם מעקב אחר תנועה אכן רגיש יותר לאפקטים לא מודעים מאשר מקלדת? עד עתה, מחקר אחד בלבד השווה בין המדדים באופן ישיר ומצא אפקט לא מודע שולי באמצעות מקלדת אך מובהק באמצעות שימוש בעכבר. אולם מדד המודעות כמו גם המערכת למעקב אחר תנועה בהם נעשה שימוש במחקר זה הינם מוגבלים. מטרת התזה הנוכחית היא לבחון האם למעקב אחר תנועה יש יתרון על פני מקלדת בכל הנוגע לגילוי אפקטים לא מודעים, תוך כדי התגברות על המגבלות הללו.

לשם כך, עשיתי שימוש במדדים מחמירים למודעות בשילוב עם מעקב אחר תנועת הושטה אינטואיטיבית בסדרה של ארבעה ניסויים. שלושה מחקרי גישוש ראשוניים נערכו על מנת לזהות את התנאים האופטימליים לגילוי של אפקטים לא מודעים באמצעות תנועות הושטה. מחקר אישוש רביעי השווה ישירות בין תנועות הושטה לבין מקלדת. ארבעת המחקרים התבססו על המחקר הקלאסי של דהאן ושותפיו (2001) שבו נבדקים סיווגו סמנטית מילת מטרה אשר עקבה אחרי מילת פריים זהה/שונה שהוצגה באופן לא מודע. הניסוי הראשון הפיק תוצאות שאינן מובהקות, כנראה בשל זמני התגובה הארוכים של הנבדקים. בניסוי השני הוטלה מגבלה נוקשה יותר על זמן התגובה אשר כללה מגבלה על תחילת התנועה ומגבלה על משך התנועה. כמו כן, ניתן בלוק אימון נוסף על מנת לשפר את זמן התגובה. כתוצאה מקיצור זמן התגובה, מספר רב של חזרות לא הושלמו בהצלחה ולפיכך נפסלו. לכן, בניסוי השלישי נוסף יום אימון נפרד שנועד לשפר את זמני התגובה של הנבדקים. אף על פי שמספר החזרות הפסולות לא פחת, בניסוי השלישי התגלה רמז להבדל בין תנאי הניסוי אשר סימל עיבוד לא מודע. בניסוי הרביעי הושמט יום האימון הנוסף ונכללו שתי מטלות נפרדות, באחת מהן נבדקים ענו באמצעות מקלדת ובשניה באמצעות תנועות הושטה. שתי המטלות חשפו אפקט לא מודע, אשר בשילוב עם המדדים הנוקשים למודעות, סיפקו עדות שאינה קלה להפרכה לקיום של עיבוד לא מודע. בניגוד לממצאים קודמים, האפקט הלא מודע במטלת המעקב אחר תנועה לא היה גדול מזה שהתגלה במטלת המקלדת. לסיום מועלות הצעות לשינויים במערך הניסוי אשר יכולים לשפר אף יותר את הרגישות של מדד התנועה לעיבוד לא מודע.

בית הספר סגול
למדעי המוח
אוניברסיטת תל אביב

בית הספר סגול למדעי המוח

הפקולטה למדעי המוח

שימוש במעקב אחר תנועה על מנת לחקור את העיבוד הלא מודע

מאת

חן הלר

החיבור בוצע בהנחייתה של

פרופ' ליעד מודריק

ספטמבר 2022