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Faculty of Brain Sciences

Show some sensitivity! Using motion tracking to explore unconscious processes

By

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בית הספר סגול למדעי המוח

הפקולטה למדעי המוח

שימוש במעקב אחר תנועה על מנת לחקור את העיבוד הלא מודע

מאת

**חן הלר**

החיבור בוצע בהנחייתם של

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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 its scope, and specifically for semantic processing. Such contradicting results can be explained by methodological limitations of some of these studies. One 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 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, and 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 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 significant congruency effect which, combined with the rigorous awareness testing, provided substantial evidence for the existence of unconscious semantic 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 (Avneon, 2018; Kouider & Dehaene, 2007), 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" on the other (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 in my 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 in 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 (Dehaene et al., 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 [ref](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 ). 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 and Psychtoolbox 3.0.18. 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 at a sampling rate of 120Hz. The coordinates were broadcasted online to a NatNet client and recorded with Matlab.

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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). 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.

Diagram

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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 (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 (2nd 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 (2nd 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 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 eight 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. Using identical primes and target words in the congruent condition biases the responses towards the target, therefore 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: The traveled distance variable as well as the movement duration and frequency of COM variables was tested with a permutation test [ref to Mattan's package] since they violated the normality assumption. After correcting all the p-values for multiple comparisons using the Tree-BH method suggested in Bogomolov et al. (2021) no significant difference was found between the congruent and incongruent conditions in any of the dependent variables (Figure 3). However, small trends were observed, specifically in the reach area which was numerically smaller in the incongruent condition (Mcon = 2.80, SDcon = 0. 47, Mincon = 2.70, SDincon = 0. 50, t(9) = 2.16, p = 0.169, 95% CI [0, 0.20]) and reaction time which was numerically longer in the incongruent condition (Mcon = 433.96ms, SDcon = 125.26, Mincon = 441.88ms, SDincon = 125.81, t(9) = -2.07, p = 0.169, 95% CI [-16.55, 0.71). The distance traveled on the congruent and incongruent conditions did not differ (Mcon = 40.88, SDcon = 1.49, Mincon = 41.06, SDincon = 1.59, p = 0.694, 95% CI [-0.51, 0. 17]) and neither did the COM frequency (Mcon = 0.21, SDcon = 0.06, Mincon = 0.20, SDicon = 0.08, p = 0.896, 95% CI [-0.02, 0.03]) or the movement duration (Mcon = 558.15ms, SDcon = 80.72, Mincon = 557.91ms, SDincon = 81.61, p = 0.896, 95% CI [-5.96, 5.60]).



Figure 3. Results of Experiment 1. (a) Reaching trajectories of correctly answered trials to left and right targets, averaged across all participants. (b-f) Dots are single participant averages while the red/blue horizontal lines are the average of all participants. Black error bars symbol the standard error (SE). Full/dashed grey lines represent a numerical incline/decline 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

Given the results of Experiment 1, an explanation is called for, which clarifies why a congruency effect did not emerge and how can the paradigm be improved to promote it. A possible explanation for the null result can be given using an evidence accumulation model as was done in Mattler & Palmer, (2012). In this model, which is used to model decision making processes, the presentation of a stimulus commences an evidence accumulation process in favor of the response that corresponds to the stimulus. 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. This is the case for incongruent trials in priming paradigms, where the prime and the target provide contradictory evidence. The delayed crossing of the threshold explains why incongruent trials often yield longer response times compared to congruent trials in priming paradigms (Dehaene et al., 1998, 2001; Dell’Acqua & Grainger, 1999). However, in my experiment the movement duration was identical for both conditions. Consequently, I reasoned that the decision is made before the movement has started. This notion was supported by the slightly longer reaction time in the incongruent condition, suggesting that participants first reached their decision threshold and only then initiated their movement. As a result, the congruency effect was not expressed in the movement itself.

Therefor in experiment 2, reaction time 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 experiment 1 considering that participants will not have enough time to make a decision before starting their movement.

### Methods

#### Participants

9 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 excluded 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: overall, 81.63% of the trials were rated as visibility 1, 16.07% as visibility 2, 1.83% as visibility 3 and 0.46% as visibility 4. When participants rated the prime as invisible, they were not better than chance at recognizing it, M = 50.26%, SD = 2.57, t(8) = 0.30, p = 0.770, 95% CI = [48.27, 52.24]. Thus, both the subjective and the objective measures suggest that masking was effective in rendering the stimuli invisible.

Congruency effect: Multiple comparisons correction was similar to Exp 1., except for the tree hierarchy, which in the current experiment separated the confirmatory reach area analysis from the rest of the exploratory variables. A permutation test was used to correct for a violation of normality in traveled distance, frequency of COM, reaction time, movement duration and reach area. Similarly to Exp 1. a congruency effect was not reflected in any of the dependent variables (Figure 4). Null results were obtained for the traveled distance (Mcon = 37.20, SDcon = 1.09, M­­incon = 37.67, SDincon = 1.17, p = 0.536, 95% CI [-1.17, 0.23]), frequency of COM (Mcon = 0.26, SDcon = 0.08, M­­incon = 0.27, SDincon = 0.12, p = 0.781, 95% CI [-0.08, 0.05]), reaction time (Mcon = 140.44ms, SDcon = 34.23, M­­incon = 144.27ms, SDincon = 33.21, p = 0.536, 95% CI [-9.62, 1.93]), movement duration (Mcon = 416.56ms, SDcon = 60.57, M­­incon = 423.96, SDincon = 45.40, p = 0.536, 95% CI [-17.63, 2.74])and reach area (Mcon = 1.50, SDcon = 0. 28, Mincon = 1.39, SDincon = 0. 64, p = 0.699, 95% CI [-0.14, 0.36])



Figure 4. Results of Experiment 2. (a) Reaching trajectories of valid trials to left and right targets, averaged across all participants. (b-f) Dots are single participant averages while the red/blue horizontal lines are the average of all participants. Black error bars symbol the standard error (SE). Full/dashed grey lines represent a numerical incline/decline between the congruent and incongruent conditions.

### Discussion

In Exp 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. Surprisingly, null results were observed for all the dependent variables. An examination of the reach area distribution shows a 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, (b)). 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 can also explain the difficulty in detecting an effect.

## 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

7 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 use in Gallivan & Chapman (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: overall, 76.29% of the trials were rated as visibility 1, 20.08% as visibility 2, 2.85% as visibility 3 and 0.76% as visibility 4. When participants rated the prime as invisible, they were not better than chance at recognizing it, M = 47.46%, SD = 3.45, t(6) = -1.94, p = 0.100, 95% CI = [44.26, 50.65]. Thus, both the subjective and the objective measures confirm that masking was effective in rendering the stimuli invisible.

Congruency effect: Multiple comparisons correction procedure was identical to Exp 2. Additionally, the movement duration variable as well as the reach area and the traveled distance variables, were tested using permutation since they violated the normality assumption. Contrary to experiment two, a significant difference was detected in the reach area (Figure 5) which was smaller in the incongruent condition (Mcon = 2, SDcon = 0.30, Mincon = 1.73, SDincon = 0.25, p = 0.023, 95% CI [0.11, 0.42], Cohen's d = 1.14). On the other hand, the congruency effect was absent in the traveled distance (Mcon = 38.27, SDcon = 1.25, Mincon = 39.23, SDincon = 1.74, p = 0.125, 95% CI [-1.40, -0.51]), the frequency of COM (Mcon = 0.20, SDcon = 0.13, Mincon = 0.20, SDincon = 0.15, t(6) = -0.05, p = 0.959, 95% CI [-0.10, 0.10]), the reaction time (Mcon = 164.46ms, SDcon = 26.10, Mincon = 175.93ms, SDincon = 15.40, t(6) = -2.22, p = 0.125, 95% CI [-24.08, 1.12]) and the movement duration (Mcon = 391.95ms, SDcon = 32.91, Mincon = 403.35ms, SDincon = 25.40, p = 0.125, 95% CI [-20.18, -3.05]). . Surprisingly, the response time between the first block of the first and the second days improved only slightly but the difference was not significant (M1 = 535.97, SD1 = 63.18, M2 = 455.76, SD2 = 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 Exp 2. And Exp 3. (M2 = 234.44, SD2 = 84.66, M3 = 162.57, SD3 = 63.23, t(14) = -1.87, p = 0.082, 95% CI [-154.25, 10.51]). . More specifically, a significant increase was found in the number of short trajectories (M2 = 14.55, SD2 = 17.59, M3 = 70.28, SD3 = 42.75, t(14) = 3.56, p = 0.003, 95% CI [22.23, 89.22]) while an increasing trend was found for the number of early responses (M2 = 36.77, SD2 = 40.96, M3 = 68, SD3 = 65.20, t(14) = 1.17, p = 0.259, 95% CI [-25.77, 88.22]). Contrastingly, and in-line with my expectations, decreasing trends were found for the number of late responses (M2 = 58.88, SD2 = 21.60, M3 = 54.57, SD3 = 28.37, t(14) = -0.34, p = 0.734, 95% CI [-31.05, 22.41]), slow movements (M2 = 9.66, SD2 = 18.06, M3 = 0.57, SD3 = 0.78, t(14) = -1.32, p = 0.207, 95% CI [--23.86, 5.67]) and incorrect answers (M2 = 72.11, SD2 = 21.22, M3 = 49, SD3 = 29.68, t(14) = -1.82, p = 0.090, 95% CI [-50.34, 4.12])..



Figure 5. Results of Experiment 3. (a) Reaching trajectories of valid trials to left and right targets, averaged across all participants. (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 standard error (SE). Full/dashed grey lines represent a numerical incline/decline 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. The results d on the reaching trajectories, as was evident by the was expressed in a 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 Exp 3. did not significantly reduce the participants' response time or proportion of excluded trials, and was therefore forgone in the next experiment.

## Exp 4

The last experiment included in this thesis was a preregistered one [ref], aimed at examining whether motion tracking is preferable over keyboard responses when studying unconscious processing. To do so, Experiment 4 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). Contrastingly to Xiao et al (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 Exp. 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 criterions were identical to those of Exp 1. 30 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 experiment 2 and 3, when using only half of the trials in each experiment. The average effect size was 0.88 (Cohen's dz). I estimated the keyboard task's effect size to be around 30% smaller (Cohen's dz = 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 three. 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: overall, 94.41% of the trials in the reaching session were rated as visibility 1, 4.79% as visibility 2, 0.63% as visibility 3 and 0.15% as visibility 4, while in the keyboard session 92.12% of were rated as visibility 1, 7.04% as visibility 2, 0.70% as visibility 3 and 0.12% as visibility 4. When participants rated the prime as invisible, they were not better than chance at recognizing it, 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 the subjective and the objective measures confirm that masking was effective in rendering the stimuli invisible.

Congruency effect: All the comparisons contrasting between the congruent and incongruent conditions were corrected for multiple comparisons with a procedure identical to that used in Exp. 1. Since reach area's residuals did not distribute normally, I used a permutation test to estimate its p-value. A congruency effect was found in both measures, as was evident by the smaller reach area (Mcon = 2.09, SDcon = 0.51, Mincon = 1.74, SDincon = 0.49, p < 0.001, 95% CI [0.16, 0.52]) and slower keyboard-RT (Mcon = 525.53ms, SDcon = 35.76, Mincon = 545.46ms, SDincon = 32.87, t(29) = -6.42, p < 0.001, 95% CI [-26.27, -13.58]) in the incongruent condition. 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 (Mcon = 38.20, SDcon = 1.44, Mincon = 39.09, SDincon = 1.67, t(29) = -5.19, p < 0.001, 95% CI [-1.25, -0.54], Cohen's dz = -0.95) and a prolonged movement duration (Mcon = 415.88ms, SDcon = 29.76, Mincon = 429ms, SDincon = 28.32, t(29) = -6.40, p < 0.001, 95% CI [-17.32, -8.93], Cohen's dz = -1.17) in incongruent trials. Contrastingly, reaction time (Mcon = 171.29ms, SDcon = 22.42, Mincon = 173.06, SDincon = 23.95, t(29) = -1.01, p = 0.318, 95% CI [-5.31, 1.79]) and the number of changes of mind (Mcon = 0.24, SDcon = 0.12, Mincon = 0.22, SDincon = 0.11, t(29) = 1.06, p = 0.318, 95% CI [-0.02, 0.06]) in the reaching session did not differ between the conditions. As predicted by Exp 2. and Exp 3. the number of excluded trials in the reaching task was high and in fact exceeded that of the keyboard task (Mreach = 128.76, SDreach = 35.52, Mkeyboard = 50.2, SDkeyboard = 14.47, t(29) = 12.70, p < 0.001, 95% CI [65.91, 91.21], Cohen's dz = 2.31). Further inspection however revealed this was true for late responses (Mreach = 32.06, SDreach = 19.24, Mkeyboard = 14.06, SDkeyboard = 10.33, t(29) = 4.71, p < 0.001, 95% CI [10.19, 25.80], Cohen's dz = 0.86) and early responses (Mreach = 23.26, SDreach = 19.79, Mkeyboard = 0, SDkeyboard = 0, t(29) = 6.43, p < 0.001 , 95% CI [15.87, 30.65], Cohen's dz = 1.17) but not for incorrect answers which were less common in the reaching task (Mreach = 21.90, SDreach = 12.33, Mkeyboard = 36.13, SDkeyboard = 15.29, t(29) = -6.31, p < 0.001, 95% CI [-18.84, -9.62], Cohen's dz = -1.15).



Figure 6. Results of Experiment 4. (a) Reaching trajectories of valid trials to left and right targets, averaged across all participants. 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. The box represents the high and low quartiles while the vertical lines mark the 1.5 \* inter quartile range. The grey line is the median and the shaded density functions are the distributions of participants' averages in each condition.

### Discussion

Experiment four utilized motion tracking and keyboard measures to probe unconscious processing. Despite previous criticisms about the robustness and reliability of evidence (Damian, 2001; Peters & Lau, 2015) a large congruency effect was found using each measure. 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 155ms to 398ms (17.5-95.5% of the path) post target onset showing that the prime exerts its effect almost throughout the entire movement. Surprisingly, the significant effect found with the reach area variable was smaller than that found with the keyboard-RT, although noticeably the reaching movement duration was not less sensitive than the keyboard-RT. Possible explanations are discussed below.

## General Discussion

Increased sensitivity to unconscious effects is necessary to settle the long-lasting debate about the extent of unconscious processing (Hassin, 2013; Hesselmann & Moors, 2015; Peters et al., 2017). Consequently I set out to examine if motion tracking can serve as a solution for the small effect sizes that are usually found in the field of unconscious processing (Greenwald et al., 1996; Van den Bussche et al., 2009).. To do so I integrated reaching responses into a classical semantic priming paradigm that was previously used by Dehaene et al. (2001) and colleagues and was proven to exhibit extensive unconscious effects. My first experiment required participants to make a semantic judgment regarding a target word that was preceded by a congruent/incongruent subliminal prime word. Analysis of the results revealed a hint of unconscious processing in the reach area variable which was smaller for incongruent trials. Since this experiment allowed for relatively slow responses, I suspected that the evidence accumulation processes ended and a final decision was reached (Mattler & Palmer, 2012) before the movement was initiated, which explains why a robust congruency effect was not reflected in the movement. Supportive evidence for this assumption was provided by the longer reaction times, but not movement durations, in incongruent trials. Considering these results, the response window in the second experiment 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, occluded the congruency effect.. To solve these problems, an additional training day was added in experiment three, which was intended to improve the participants' response speed and increase the number of valid trials. Consequently numerically lower RT was observed in the second day of Exp 3. And a significant congruency effect was detected in the reach area variable. Surprisingly, the additional training day did not increase the number of valid trails and was therefore omitted in Exp 4. The goal of the fourth experiment was to examine if motion tracking is superior to keyboard-RT when probing unconscious processing, consequently both measures were used in two consecutive sessions, both of which yielded robust effects.

Since the experiment included stringent awareness measures, criticisms attributing unconscious effects to residual undetected awareness (Merikle, 1992; Peters & Lau, 2015; Zerweck et al., 2021) should not apply for these results. Similarly, the unconscious effect does not stem from regression to the mean of the awareness measurement [ref to shanks 2017] since no participants were excluded because they saw the prime. Furthermore, the distribution of the objective awareness measure is centered around 50% correct answers [ref to figure] which indicates that the masking manipulation was successful. To conclude, the observed unconscious effect is not easily refuted and therefore provides a solid testimony for unconscious processing in the debate regarding its extent (Hassin, 2013; Hesselmann & Moors, 2015; Peters et al., 2017).

My experiment demonstrated why motion tracking can be beneficial to the study of unconscious processes. Unlike keyboard response, which is definitive and final, the reaching measure allows participants to change their mind while providing the answer and correct it if necessary. This type of behavior is particularly interesting because it might reflect a strong conflict between and incongruent prime and target. Additionally, the possibility to regret and correct could decrease the number of incorrect answers as was demonstrated in Exp 4.

Although I expected the keyboard session to produce a smaller effect, in practice its size was comparable to that found in the movement duration variable. Conversely, the effect size of the reach area measure was smaller than that of the keyboard. One possible explanation for this pattern of results is provided by the larger amount of noise in the reaching measure which decreased its SNR. Specifically, reaching movements require planning a trajectory in space towards a target which makes them more complex, and the more complex a process is, the more room there is for error and variability when executing it. Hence, the expression of a congruency effect in a complex reaching movement might be less consistent across participants when compared to a simple keypress. This 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). The SNR was further decreased in the reaching session due to the higher number of excluded trials.

An alternative explanation of the results suggests that unconscious processing does not exert its effect over reaching responses as well as it does over keypresses. The reason being that unconscious effects are short-lived (Greenwald et al., 1996) while reaching responses are a relatively long ongoing procedure. However, this interpretation does not conform with the clustering results which show that primes exert their effects almost throughout the entire movement. In addition, given that the reaction times of the two measures differ in only 60ms (Mreaching = 594.62, Mkeyboard = 535.49) this explanation seems unlikely.

Finding a similar effect size for the keyboard and the reaching measures does not fall in line with the effects discovered by Xiao et al. (2015) which showed an advantage for mouse tracking over keyboard responses. The simplest explanation for this discrepancy is that mouse tracking is more sensitive than reaching responses. Then again, it does comply with the more intuitive use of reaching which places less constraints on movements (Desmurget et al., 1997; Palluel-Germain et al., 2004) and with previous findings that showed reaching responds faster and with greater curvatures to changes of mind (Moher & Song, 2019).

Notably, the current study differs from the one conducted by Xiao et al. (2015) by the parameter that was extracted from the trajectories. While I used an area measure that is calculated using the average trajectories, and therefor produces a single value per participant, Xiao et al. used Area Under the Curve (AUC) which is computed separately for each trial. This type of measure might include much of the variance I that is lost when averaging trajectories over trials. However, a post hoc analysis of the AUC measure on my data reveled similar effect size to that produced by the reach area measure.

Alternatively, a different explanation can be conceived when examining the objective measure results reported by Xiao et al. [ref]. The awareness was assessed 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' reveals that the masking procedure was unable to render the prime completely invisible, allowing it to be consciously processed. It is plausible that consciously processed primes affect movements to a larger extent than unconscious ones, which could account for the large effect found by Xiao et al.

Finally, the discrepancy could also be due to accidental findings. Further studies will have to examine the relation between reaching and keyboard responses. One augmentation possible for future studies would be to use a dynamic starting condition in which the stimuli is 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, the number of excluded trials will decrease with such paradigm 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.

Ideas for content:

This paper claims averaging trajectories is wrong. Read it before the thesis test:

Wulff (2019). Mouse-tracking: Detecting types in movement trajectories

Friedman (2013). Linking cognitive and reaching trajectories via intermittent movement control – Friedman's paper that claims that the motor access to the cognitive processes is intermittent instead of continuous. This could affect my experiment.

Schmidt (2007). Measuring unconscious cognition: Beyond the zero-awareness criterion - Check if this paper has some conclusions about "reaching" that can be relevant for your discussion

Distinct mechanisms for planning keypress and reaching responses: A developmental study – Read this, they show keyboard and reaching operate under different mechanisms.

Make sure all references appear in bibiliography