**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, an ongoing controversy about the scope of such processing is repeatedly evoked by a multitude of contradicting findings. This controversy can be explained by the use of insensitive measures of the unconscious effect, the most prominent being reaction time (RT), as measured using keyboard presses. This measure usually produces very small effects and indexes the final decision but not the process of formulating it. Both these problems might be solved by using motion tracking, which has become a popular tool for unraveling cognitive processes. Yet, the only study that directly compared keyboard responses to motion tracking and found the latter to be advantageous, suffers from limitations to its awareness and motion tracking measures. Here, to overcome the aforementioned limitations, a set of rigorous awareness measures and an intuitive reaching response were introduced to a priming paradigm that followed a classical study by Dehaene and colleagues (2001). In separate keyboard and reaching sessions, subjects performed a semantic judgment on a target word that was preceded by an identical/different invisible prime. 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. However, unlike the previous finding, the unconscious effect in the motion tracking task was only slightly larger than in the keyboard task. Possible explanations are discussed as well as suggested augmentations to the paradigm which could improve motion tracking's sensitivity even further.

## Introduction

Our brain continuously processes information. It receives inputs via our senses and processes them 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 in 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 stimulus 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). 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 for the processing of the prime (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 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 threshold (Eriksen, 1960; Hannula et al., 2005). For the objective measure, the participant is asked to make an objective judgment 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 to 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 into 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 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 that 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 into 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).

### Priming and 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 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 of 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 were 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 keyboard RTs, yet without directly comparing 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 the mask was 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 toward 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 therefore 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, rounded 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 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) consequently suppressing the expression of cognitive conflicts. Indeed, when both measures were compared, reaching produced shorter reaching 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 the effects of unconscious processing. To do so, both measures were compared on an identical priming task. This approach followed the one by Xiao et al. (2015) but replaced the mouse response with a more intuitive and less effortful reaching response that does not constrain free movement (Desmurget et al., 1997; Palluel-Germain et al., 2004). Additionally, it improved the validity of the unconscious results by applying a rigorous awareness detection procedure that included 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, here awareness was estimated in the trials of the main task. The priming paradigm emulated 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 that 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. The reaching task was expected to express the congruency effect so that the average reaching trajectories of the incongruent trials would deviate toward the incorrect answer further than would the trajectories of the congruent trials. In the keyboard task, the incongruent trials were expected to exhibit longer response times (RTs). h,effect found in the was expected to be effect in the

### Methods

#### Participants

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. had e The sample size was determined following a power analysis based on the average of the effects of two pilot experiments that are not reported in this paper. The average effect size was 0.88 (Cohen's dz; see Lakens, 2013). The keyboard task's effect size was estimated to be around 30% smaller (Cohen's dz = 0.61), in line with the 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 an 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).

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#### Procedure

Two main sessions were conducted on the same day with their order counterbalanced between participants. One session 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). Breaks were given between blocks. The procedure within each block closely followed the one used by Dehaene et al. (2001). 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 selecting the side of the screen that contains the appropriate category (Figure [ref]). Following the guidelines set up by Gallivan & Chapman (2014), in the reaching session the finger had to leave the starting point within 100ms-320ms post target presentation and then reach the screen within 420msThe finger left the starting point when it1it reached the screen 0.7the screenEarly or l,as well as,"Too Early", 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. To avoid interrupting the participant's movement, the "Too slow" feedback was given after the movement was completed. In the keyboard task, participants pressed the "E"/"Y" keys with the left/right hand to select the left/right side accordingly. The response had to be given within a time window of 100-740ms from the target display, otherwise "Too Early"/ "Too Late" feedback was given. 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. The response was given in an identical fashion to the target classification task, within a 7 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.

The word stimuli included natural and artificial items so that half of the targets described natural items and half artificial items. Stimuli order was dictated by a list that was randomly sampled (without replacement) out of twenty pre-composed lists of trial condition and stimuli in the experimental blocks and ten precomposed lists in the practice blocks. In each list, the order of words was pseudorandom, with the following constraints: (a) In the congruent condition the prime was identical to the target word; (b) 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"; (c) Half the trials were congruent and half incongruent; (d) Each word was equally frequent as a target at the congruent and incongruent conditions; (e) All words were used as targets the same number of times; (f) A target never repeated in the same block. 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.

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. Additional problematic responses were "Too Early" and "Too Late" trials. "Too Slow" trials on the other hand, were excluded only if they were located more than 3 SD from the participant's average reaching 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.



21007407 In practice, the blue circle and the Artificial/Natural category names were presented on the screen from the beginning of the trial, but for clarity purposes are presented here only after the last mask.

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#### Analysis

All the comparisons between the congruent and incongruent conditions were corrected for multiple comparisons using the Tree-BH method (Supplementary Figure [ref]) suggested in Bogomolov et al. (2021). The 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 [ref]).

Three comments received from colleagues after the submission of the pre-registration document prompted additional analyses. The first addresses the high variability between participants which can obscure smaller but highly consistent effects. To tackle this issue, the non-timeseries variables were normalized within participant. Both the original and the normalized analysis results are provided in Table [ref], but only the normalized are discussed in the results section below. The second comment acknowledged the importance of the congruency effect's temporal aspect, which can be accessed only when avoiding spatial normalization. To average the non-normalized trajectories, all trials had to be trimmed to an identical length of 340ms. Ninety percent of the trials were 340ms long or longer, and the other 10% were excluded. To approximate the onset and offset of the congruency effect the deviation from the center was estimated for each point in time. The third comment stressed the examination of horizontal velocity and implied endpoint since they are sensitive to changes in direction and should therefore reflect the participant's intentions earlier than the raw trajectory [ref]. Horizontal velocity was derived by dividing the distance along the X-axis between each two points by the sampling rate, while the implied endpoint was indicated by the intersection between the present tangent to the trajectory and the screen. The congruency effect's onset and offset were estimated by conducting a t-test at every time point, and clustering together adjacent significant values of the similar sign. Then a permutation and clustering procedure [ref] was conducted to evaluate the clusters' significance and correct for multiple comparisons. Finally, the value was divided by three to correct for the three permutation and clustering procedures performed (i.e., deviation from center, velocity, and implied endpoint).

### 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. the incongruent trials were used to Objective recognition performance for the subjectively invisible stimuli was not better than chance, 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 with both measures. In the reaching task, the reach area, which is 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, was smaller in the incongruent condition. In the keyboard task, slower RT was observed in the incongruent condition (Table [ref]). A 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 = 0.68). However, reaching duration, which was longer for incongruent trials, produced the largest effect (Cohen's d = 1.25). Furthermore, incongruent trials exhibited a greater traveled distance, determined by adding up the Euclidean distances between all adjacent samples within a single trial. On the other hand, reaction time, defined as the time from stimulus presentation up to movement onset, did not differ between the conditions. Examination of the implied endpoint revealed that changes of mind occurred slightly more often in the incongruent condition. A change of mind was registered every time the implied endpoint crossed from one side of the screen to the other.

Although the average time-dependent trajectories deviated towards the incorrect answer in incongruent trials, the bias was not statistically significant. However, horizontal velocity and implied endpoint did produce a significant congruency effect[ref]. After reaching onset, congruent trials had a higher horizontal velocity between 150-300ms (p < 0.001, Cohen's dz = 0.74), and their implied endpoint was more laterally oriented between 150-340ms (p = 0.001, Cohen's dz = 0.71).

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 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 [ref]).

**Table 1**

*Congruency Effect in the Reaching and Keyboard Sessions*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Congruent** | **Incongruent** |  |  |  |  |
|  |  | **M (SD)** | **M (SD)** | **t(29)** | **p** | **CI** | **d** |
| **Reaching** | | | | | | | |
|  | **Reach area** | 2.09 (0.51) | 1.74 (0.49) | 3.75 | <0.001\* | 0.15, 0.53 | 0.68 |
| **Traveled distance** | 38.20 (1.44) | 39.09 (1.67) | 5.19 | <0.001\* | -1.25, -0.54 | 0.94 |
| **Reaction time** | 171.29 (22.42) | 173.06 (23.95) |  | 0.318 | -5.12, 1.58 | 0.19 |
| **Reaching duration** | 415.88 (29.76) | 429 (28.32) |  | <0.001\* | -17.08, -9.17 | 1.17 |
| **COM** | 1.77 (0.40) | 1.99 (0.48) |  | 0.02\* | -0.39, -0.05 | 0.46 |
| **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 p-value corrected for multiple comparisons; CI = 95% confidence intervals; d = Cohen's d.  \* p < p-value for after adjustment according to the Tree-BH method. | | | | | | | |

**Table 2**

*Congruency Effect in the Reaching and Keyboard Sessions, Normalized within Participant*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Congruent** | **Incongruent** |  |  |  |  |
|  |  | **M (SD)** | **M (SD)** | **t(29)** | **p** | **CI** | **d** |
| **Reaching** | | | | | | | |
|  | **Traveled distance** | -8.79 (15.55) | 16.13 (17.06) | 4.82 | <0.001\* | -35.49, -14.36 | 0.88 |
|  | **Reaction time** | -7.23 (96.02) | 43.09 (107.69) |  | 0.161 | -119, 17.90 | 0.26 |
|  | **Reaching duration** | -76.53 (132.92) | 185.76 (108.72) |  | <0.001\* | -335.79, -188.56 | 1.25 |
|  | **COM** | -0.09 (0.23) | 0.12 (0.27) |  | 0.022\* | -0.39, -0.05 | 0.46 |
| **Keyboard** | | | | | | | |
|  | **Response Time** | -121.72 (115.81) | 151.84 (121.60) | 6.49 | <0.001\* | -359.66, -187.48 | 1.18 |
| *Note.* t(df) = t-test score, only for variables whose residuals distributed normally. Degrees of freedom are in parenthesis; p = Tree-BH p-value corrected for multiple comparisons; CI = 95% confidence intervals; d = Cohen's d.  \* p < p-value for after adjustment according to the Tree-BH method. | | | | | | | |

**Figure 3**

*Results for the Space-Normalized Trajectories*



*Note.* Measures in the figure were not normalized within participant.(a) Reaching trajectories in valid trials , averaged across participants. Shaded areas are the SE. (b-f) Dots are single-participant averages across valid trials, while the red/blue horizontal lines are the average of all participants. Black error bars symbolize the SE. Full/dashed grey lines represent a numerical incline/decline (respectively) between the congruent and incongruent conditions.

**Figure 4**

*Time-Dependent Results*



*Note.* Time-dependent trajectory, velocity, and implied endpoint. Instead of normalizing the trajectories to the Z-axis, valid trials were trimmed to 340ms and then averaged across participants. The shaded areas mark the standard error (SE) while grey rectangles highlight the time range where a significant difference between the conditions was detected using the permutation and clustering procedure.\* The first 100ms of the implied endpoint figure indicate participants tended to initiate their movement towards the left. This outcome may be attributed to a motor artifact caused by positioning the right reaching arm near the center of the body.

**Figure 5**

*Trajectories of Two Participants*



*Note.* Reaching trajectories of valid trials. The trajectories here are not normalized within participant and the thin lines represent single trials while thick lines are the averages. (a,c) Belong to participant 53m while (b, d) belong to participant 59.

## 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 effect sizes that are usually found in the field (Greenwald et al., 1996; Van den Bussche et al., 2009). This study 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, motion tracking was introduced to a variant of the classical word repetition priming paradigm previously used by Dehaene et al. (2001). This allowed tracking participants' reaching responses as they performed a semantic judgment (i.e., determine whether the word described a natural item or a man-made artifact) on a visible target word that was preceded by an invisible prime. To compare reaching's sensitivity to more prominent measures, each participant completed an additional session using keyboard responses.

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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, presenting an incongruent prime biased the participant's responses towards the incorrect answer, resulting in average trajectories that curve towards the center of the screen. The area between these trajectories was smaller than between the congruent ones, providing quantifiable evidence for the invisible prime's effect on movement. Temporally, this effect can be placed approximately between 160-300ms post target presentation, as depicted by the velocity and implied endpoint measurements (note however that this analysis should not be taken as evidence for the exact latency/offset of the effect; see Sassenhagen & Draschkow, 2019). The curved trajectories of the incongruent trials were longer than the congruent trajectories and took longer to complete, reflecting the prime's interference with the participant's decision-making. The results go beyond previous studies, as the current design included stringent awareness measures, with trial-by-trial subjective and objective measures, therefore addressing previous criticisms that attribute unconscious effects to residual undetected awareness (Merikle, 1992; Peters & Lau, 2015; Zerweck et al., 2021). Additionally, 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 could 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). Evidence that the decision occurs during the movement and not before is provided by the reaching onset and reaching duration measurements. Had the decision been made before the reaching was initiated, the prime-target congruency would have been expected to influence the onsets, however this is not the case. Instead, a difference is found between the durations, testifying that the decision process coincides with the movement. Although monitoring the decision process allowed capturing interesting events such as changes of mind and online corrections of response, they were not expressed in the averaged trajectories. Therefore Figure [ref] provides a sample of trials depicting this indecisive behavior, which was more common in the incongruent condition. COM 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 is reduced, as was indeed the case in the motion tracking session compared with the keyboard session (though notably, there more trials were excluded due to early or late responses).

Contrary to the predictions, the effect size in the keyboard condition was only slightly smaller than that found for the reaching duration variable, and numerically larger than the effect found for the reach area measure. This result does not align with the finding of Xiao et al. (2015), which suggested a dramatic advantage for mouse tracking over keyboard responses. This discrepancy might stem from the different forms of movement tracking used in each study; while the current experiment used camera-based 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 since it places fewer 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 the current study used the reach area measure, which is calculated on the average trajectories with a single value per participant, Xiao et al. [ref] 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 that estimated the AUC measure for the current data revealed similar effect size to that produced by the reach area measure (for a full description of the results, see Supplementary Material [ref]). 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 perceived. Thus, it seems plausible that the reported effect is mainly driven by consciously processed primes, which might affect movements to a larger extent than unconscious ones and could account for the large effect found by Xiao and colleagues.

Finally, the discrepancy between the studies could also be accidental. It is plausible that one set of reported results is erroneous, thereby calling for further investigations of 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 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 ask how can they be explained. That is, why was movement tracking's effect only slightly larger than that of the keyboard response? One possible explanation concerns the larger amount of noise that was observed in the reaching measure. Specifically, reaching movements are more complex than a simple keypress as they could potentially be affected by a multitude of parameters that do not influence keypresses (e.g., trajectory planning, muscle exhaustion, arm length and posture, and so forth). A larger amount of free parameters leaves more room for variability when executing the response, which might obscure the congruency effect. 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.

An alternative explanation for the results is based 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. Evidence supporting this this interpretation resides in the cluster-based permutation results which show that the primes exerted their effects approximately between 150-340ms post reaching onset, which extends only over 45% of the total average reaching duration (422ms).

A third explanation for the results pertains to the low difficulty of the priming task at hand. Considering the low proportion of incorrect answers, it could be that the participants were at ceiling performance. Having an upper barrier to the results may diminish the difference between the conditions, thereby reducing the found effect. To increase the effect, future investigations should apply a more complex task that will decrease the participants' performance and allow for a larger gap between the conditions [ref].

The outstanding effect sizes that were found here are uncommon to unconscious priming literature [ref] and possibly originate from the short response windows that were applied. Unconscious effects have been shown to diminish over time and therefore be largest for short RTs [ref]. Indeed, a comparison of the current study's keyboard session with Dehaene [ref] reveals that although a similar experimental procedure was used, the average RT observed here was approximately 80ms shorter, and produced a larger effect. Taken together, these results stress the benefit of using short response windows in experiments that probe unconscious processes.

To conclude, although only a small 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 for delving into the temporal aspects of unconscious effects on behavior. When taken together, these results should encourage researchers to further explore the features and potential of movement tracking as a tool for studying unconscious processes. New analyses and parameters should be devised and extracted from the trajectory data to potentially expand our knowledge of processes taking place without consciousness.

## Declarations

### Funding

This study was funded by the CIFAR, Brain, Mind, and Consciousness program.

### Conflicts of interest

All authors declare that they have no conflicts of interest.

### Ethics approval

This study was conducted in accordance with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Tel Aviv University (02/01/2022, Ethics approval No. 1-0004328).

### Consent to participate

All participants signed an informed consent to participate in the study.

### Consent for publication

Informed consent to publish their data was received from each of the participants.

### Availability of data and materials

This study was preregistered (<https://osf.io/8dsvp>), its materials and data are available in the GitHub repository, [ref].

### Code availability

All the scripts used to produce this experiment and analyze its results are available at [ref to GitHub].

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## Supplementary materials





Supplementary Figure . 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 . 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 . 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 . 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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* 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.