



When did it happen? Verbal information about causal relations affects time estimation

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ABSTRACT

Usually, the closer two events occur, the more likely people infer a causal relationship between them. Recent studies have shown that this relationship between time and causality is bidirectional. Participants also tend to judge events closer in time if they assume that they are causally related. We present six experiments showing causal binding, but unlike other experiments, participants do not emit any motor action, and no physical feedback is given. Rather, all stimuli and causal information are provided verbally. After reading a list of events, participants were asked to estimate the time elapsed between two of them. Those participants who were informed that there was a causal relationship between the two events estimated them as occurring closer to each other. These results support causality- and heuristic-based explanations of temporal binding, as opposed to other explanations such as sensory integration or intentionality of action.

1. Introduction

It is well known that the temporal contiguity between two events modulates how the relationship between them is learned. For instance, inferring a causal relationship between two events is more likely when these events occur close in time than when they are distant from each other (e.g., [Schneiderman & Gormezano, 1964](#); [Shanks et al., 1989](#); [Vandercar & Schneiderman, 1967](#)). However, in recent years, experimental research has shown that this relationship between contiguity and causality is bidirectional: the estimated time interval between two events is also modulated by causal inferences about them (e.g., [Bechlivanidis & Lagnado, 2016](#); [Moore & Haggard, 2008](#); [Matute et al., 2017](#); [Moore et al., 2009](#)). More specifically, it has been shown that when people assume that there is a causal relationship between two events, they tend to subjectively compress the time elapsed between those events as if they had occurred closer to each other. This effect has been called causal binding ([Buehner & Humphreys, 2009](#); [Buehner, 2012, 2015](#); [Moore et al., 2009](#)).

One of the experimental paradigms most widely used to study causal binding is Libet's clock ([Cubillas et al., 2020](#); [Garaizar et al., 2016](#); [Haggard & Clark, 2003](#); [Libet et al., 1983](#); [Render & Jansen, 2021](#)). On each trial of this paradigm, a clock face with an inner rotary dot is presented to the participants. Then they are asked to act at any moment they wish, usually by pressing the spacebar of a computer's keyboard. Some milliseconds after their action occurs, a tone sounds. At the end of each trial, participants must indicate on the clock face the point at which the dot was when they performed the action or when the tone sounded. As previously mentioned, participants tend to miss-estimate the moment of their action and the moment at which the tone sounded, making them appear closer

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to each other than they were. In contrast, when the experimental conditions do not prompt participants to infer a causal relationship between action and tone, their judgments are more accurate, showing no binding effect (e.g., Buehner, 2012; Buehner & Humphreys, 2009; Haggard, Clark, & Kalogeras, 2002; Moore et al., 2009; Moore & Haggard, 2008).

Although Libet's clock is the most frequently used experimental paradigm, other procedures have also been used in the study of binding effects (e.g., Blakey et al., 2019; Desantis et al., 2012; Engbert & Wohlschläger, 2007; Pascolini et al., 2021; Siebertz & Jansen, 2022; Scott & Chiu, 2021). These tasks are based on trial-by-trial learning procedures in which participants personally experience the relationship between their action and the tone. The experiments are programmed so that participants experience the two events during several trials and then they infer a causal relation between them or not.

However, humans can acquire information not only through direct experience with the events but also through verbal information (e.g., Lovibond, 2003; McNally, 1981; see also De Houwer, 2014). In other words, people often learn about the occurrence of events and about their potential causal and temporal relationships, without direct physical experience with them, just by reading or by listening to others. Thus, one might expect that, as in a standard trial-by-trial procedure in which participants can directly experience the events and misinterpret the time elapsed between them when they are causally related, causal information presented through verbal narrative about the two events could also influence the temporal estimations that people make.

Some previous studies have used verbal instructions to inform participants about the causal relationship between two events, while participants were physically experiencing the events. For example, Dogge et al. (2012) induced participants to believe (through verbal instructions) that an involuntary keypress caused a tone and found that participants estimated the two events as occurring closer in time than participants that were not instructed about a causal relationship. Moreover, Faro (2010) showed that participants judged two events (i.e., their listening to a piece of music and their performance in a Rorschach task) as closer to each other if they received verbal information about the existence of a causal relationship between them. Although these two studies used verbal instructions to induce the belief that there was a causal relationship between the events (and this influenced the estimations of time), the participants in those studies did experience the events and the time lapse between them directly. These results suggest that verbal causal information modulates the time estimation of experienced events. However, our goal is to study whether verbal information about causality can also modulate the estimation of time even when participants have no physical experience with the events or with the time lapse between them, in our attempt to study how causal information affects the estimation of time when the information is presented verbally. This should reproduce the way that time estimation often takes place in real life, with people learning about events, their timing, and their potential causal relationships through the narrative of others.

Faro et al. (2005) published research in this direction. They showed that participants tend to estimate closer two historical events when they believed that they are causally related. For example, participants could estimate that "Russians launch Sputnik, the first satellite to circle the earth," was closer in time to "Neil Armstrong is the first man to walk on the moon" than to "Woodstock Music Festival". However, Armstrong's walk on the moon and Woodstock both occurred in the same year. Although participants in this experiment did not physically experience the events or learned the causal relationship between them through a direct trial-by-trial procedure, we found several methodological aspects in this study that do not allow us to respond to the question of whether the estimation of time can be manipulated through verbal information on causality. Firstly, Faro et al. (2005) showed participants historical events and therefore there is no possible randomization of the causality relations between events, which makes the study quasi-experimental. Even when the researchers informed participants verbally about the causal relation (or not) between the historical events, it appears that this information only slightly modulates the main effect of the previous information that participants had about causality (see Experiment 2, Faro et al., 2005). In addition to the methodological concerns the quasi-experimental design entails (see Andrade, 2021), the results observed by these authors could be asymmetrically affected by some variables. For example, estimating when an event has occurred is affected by several factors such as, for instance, how likely it is to reoccur (Si et al., 2016), how complex it is (Zakay & Block, 1997), or whether it has provided a greater contextual change (Zakay & Block, 2004), among others (see also Kaju & Maglio, 2022; Tu & Soman, 2022; Zauberman et al., 2010). Finally, these experiments did not control for some factors that could affect the participants' temporal judgments, such as, for instance, the previous knowledge that participants have about the historical events used in the task, as well as how and when participants acquired this knowledge. Therefore, although the results of Faro et al. (2005) are highly suggestive, some methodological concerns affect their validity.

The purpose of the six experiments presented herein is to explore the causal binding effect using an experimental design and a paradigm in which participants do not directly experience physical stimuli or the time elapsed between them, do not observe other people exposed to the events, and are not exposed to information that allows them to infer causality. Instead, the information is presented verbally, with the aim to simulate how people learn about the causal and temporal texture of their environment through written information. Furthermore, we presented the information not in a trial-by-trial format leading participants to infer causality, but in one single sentence in which we informed them verbally about the causal relationship between the events. Thus, we tested the influence of verbal information on causality on time estimation. It is important to note that the differences in the methodology discussed above may cause the processes involved in time estimation to be different in this preparation than in traditional experimental paradigms such as Libet's clock. We will elaborate on this in the general discussion.

1.1. Overview of experiments

We conducted six experiments to investigate whether verbal information affects time estimation when there is no opportunity to physically experience the events and the time elapsed between them. For this purpose, we designed a task in which participants read a list of fictitious events that occurred during the working day of a fictitious individual. After reading the information about all the events on this person's day, the participants were informed (or not) that there was a causal relationship between two of these events (*event cue*

caused *event outcome*). Finally, all participants estimated the time that had elapsed between those two target events, cue and outcome. According to previous results of causal binding studies, we hypothesized that participants who were informed about the causal relationship between the two target events would estimate that they occurred closer in time to each other than participants who were not informed about the causal relationship. Experiments 1A and 1B explored the main effect of this manipulation, while Experiments 2A, 2B, 3, and 4 extended these results and tested some alternative explanations.

1.2. Ethics statement

Before starting the experiments, participants were informed that their participation was anonymous and voluntary. We did not use cookies or external tools to obtain any personal data. Only in Experiment 4 did we ask participants about their age and gender. In Experiments 1–3, no sociodemographic data were collected. All stimuli were harmless and emotionally neutral. Participants could leave the experiments at any moment should they wish to, and at the end of the experiment, they could choose whether or not to submit their data. The ethical review boards of Universidad Autónoma de Madrid and Universidad de Deusto examined and approved the procedure used in this research.

1.3. Transparency and openness

We are reporting all measured variables, how we determined our sample size, data exclusions, and all manipulations. The materials used in these experiments are shown in Appendix A. The raw data and the commented script are available on the OSF at <https://osf.io/bg672/>. These experiments were not preregistered.

2. Experiment 1A

In Experiments 1A and 1B, we explored the causal binding effect without the presence of any physical event such as the participants' action, or a tone or light as feedback for the action. For this purpose, we asked participants to read a list of fictitious events on the computer screen. All these events were framed in a fictitious cover story and were presented as sequential events that occurred during a working day of a fictitious laboratory technician (see Appendix A). Two of the events were the target events — cue and outcome — and they were presented in an intermixed fashion with other filler events. The entire list of events was identical in all conditions. Moreover, the order in which the events appeared was constant across all groups in both Experiments 1A and 1B. After reading the list, half of the participants were told that there was a causal relationship between the two target events (Causal groups), and the other half were not (Non-Informed groups). Then, at test, all participants were informed about the moment in which one of the target events occurred and we asked them to estimate the moment of occurrence of the other target event. In this experiment, the information we presented at test was the actual moment of the occurrence of the cue (AMC) and the time that the participants were asked to estimate was the moment of the occurrence of the outcome (EMO). The dependent variable in all cases was the participants' estimation of the time that had elapsed between the two target events in minutes. In the present experiment, this variable was computed as the difference between the estimated moment of the outcome and the actual moment of the cue, that is, EMO minus AMC. Therefore, lower scores indicate that participants estimated the target events as closer to each other. As mentioned, we hypothesized that the Causal group would estimate the target events as occurring closer in time to each other than the Non-Informed group, thus showing a causal binding effect when estimating the moment of the outcome.

Table 1
Design summary of the experiments.

Experiment	Groups	Potential Cause	Test
1A	Causal	Willow leaf intake	EMO
1B	Non-Informed		EMC
2A	Causal	Willow leaf intake	EMO
2B	Non-Informed Non-Causal		EMC
3	Causal Outcome	Alphanumeric	EMO
	Non-Informed Outcome		
	Causal-Cue		EMC
	Non-Informed Cue		
4	Causal Outcome	Alphanumeric	EMO
	Non-Causal Outcome		
	Causal-Cue		EMC
	Non-causal Cue		

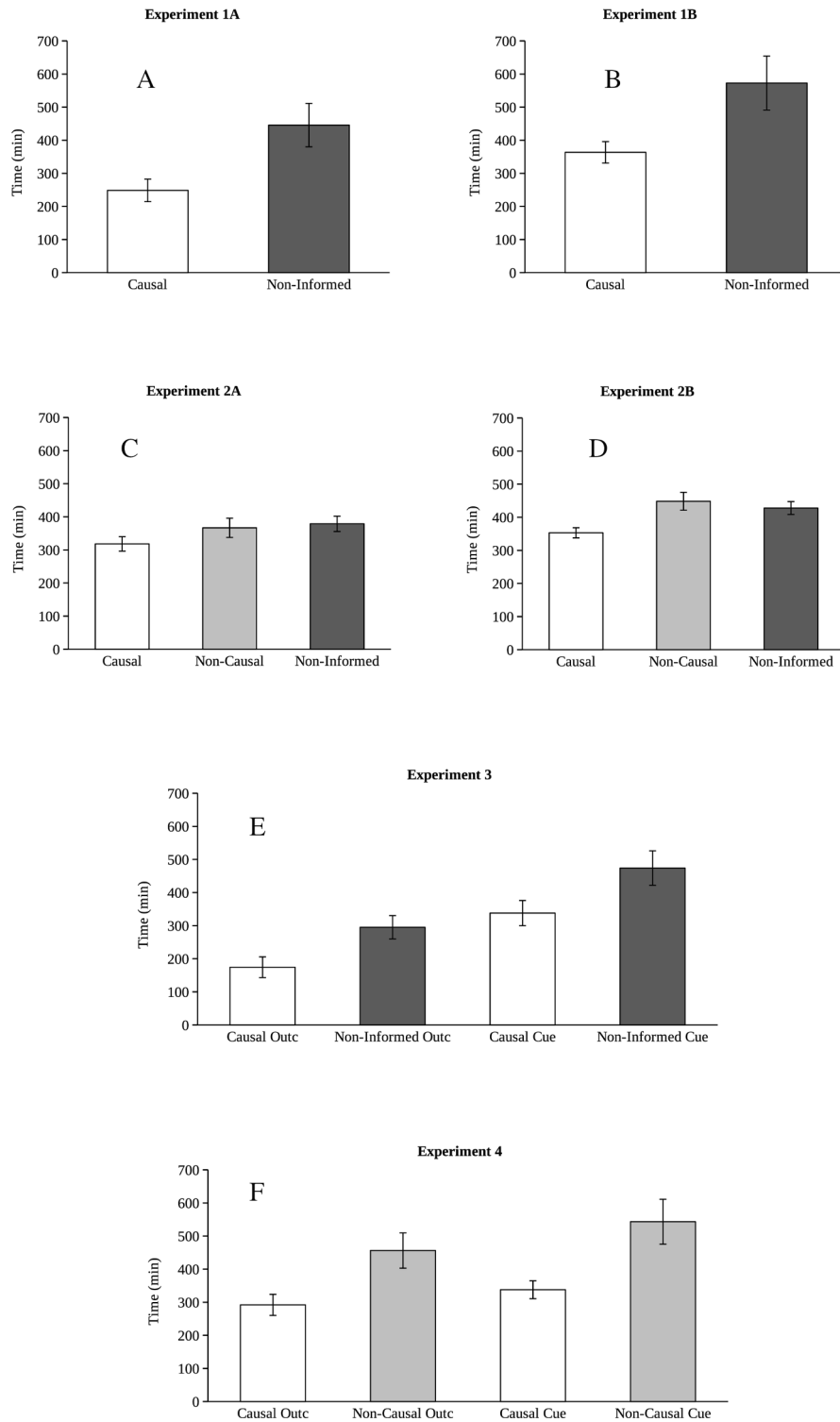


Fig. 1. Mean estimated time elapsed between the target events in each of the six experiments, in minutes. In all experiments, white bars represent the groups who were informed about the causal relationship between cue and outcome (Causal groups). Black bars represent those groups that were not informed about the causal relationship (Non-Informed groups). Gray bars represent the groups that were informed about the non-causal relationship between cue and outcome (Non-Causal groups). In Experiments 1A, 2A, and Outcome groups of Experiments 3 and 4, participants estimated the moment of the outcome (EMO). In Experiments 1B, 2B, and Cue groups of Experiment 3 and 4, participants judged the moment at which the cue appeared (EMC). Error bars represent the standard error of the mean.

2.1. Method

2.1.1. Participants

A total of 68 undergraduate psychology students from Deusto University participated in this experiment. The participants received course credit for their participation. The computer program randomly assigned them to one of two groups (i.e., 35 were assigned to the Causal group and 33 to the Non-Informed group). A *post hoc* sensitivity analysis revealed that, with this sample size, we obtained a power of 0.80 to detect an effect of $d_s = 0.72$.

2.1.2. Procedure and design

After reading the instructions, participants read a list of events that a fictitious laboratory technician had noted in the record book during one working day (see Appendix A). Each event was presented to participants on a different screen. After reading the entire list of events, participants in the Causal group were told that two of these events — the cue and outcome events — were causally related. This screen informed them that feeding guinea pigs with willow leaves (cue event) caused extreme hyperactivity in the animals (outcome event). Participants of the Non-Informed group did not receive this information. After this, all participants were asked about their EMO using an hh:mm format. We presented the AMC (08:32) on this test screen to help participants estimate the time that had elapsed between the cue and the outcome. A design summary of this experiment is presented in Table 1.

It is important to note that the only difference between groups Causal and Non-Informed was the sentence including causal information that was given to the Causal group just before the test question. It is also important to note that participants did not receive any other information about when any of the other filler events took place. Therefore, they necessarily had to base the EMO only on the AMC.

2.2. Results and discussion

As already mentioned, the dependent variable was calculated as the difference between AMC and EMO in minutes. However, some participants judged the EMO to be the same as the AMC; that is, they estimated that the cue and outcome events had occurred at the same time (08:32). This finding could be interpreted in three different ways. First, it could mean that participants estimated that 24 h had elapsed between cue and outcome. In this case, for these participants, the dependent variable should be recorded as 1440 min. Second, it could mean that participants judged that the cue and outcome happened simultaneously on the same day, in which case the value of the dependent variable should be 0. Finally, it is also possible that some participants misunderstood their task and estimated the moment of the cue instead of the moment of the outcome. To avoid this controversy, we decided to remove from the analysis the data from those participants that estimated the occurrence of the cue and the occurrence of the outcome as being simultaneous. Therefore, the dependent variable can take any value between 1 and 1399 min. Following this criterion, two participants of the Causal group and three of the Non-Informed group were excluded from the analyses. Panel A of Fig. 1 displays the results of this experiment. As can be seen in this figure, the participants of group Causal estimated the target events as being closer to each other ($M = 248.52$, $SEM = 34.14$) than participants in the Non-Informed group ($M = 445.70$, $SEM = 65.57$). A *t*-test revealed a significant difference between the two groups, $t(61) = 2.62$, $p = .011$, $d_s = 0.66$.

These results extend the results reported in studies that employed other methodologies in which participants experienced the events and inferred causality from their own experience. In the present experiment the binding effect took place when estimating the occurrence of the outcome from verbal information and in the absence of direct experience. In Experiment 1B we will test whether a similar effect also occurs when estimating the occurrence of the cue from verbal information.

3. Experiment 1B

Some previous experiments have shown that there may be differences in binding when participants are asked to estimate the time of the first or second event (e.g., Tanaka et al., 2019; Tonn et al., 2021; Wolpe et al., 2013). These differences may suggest that the two types of binding (cue binding and outcome binding) are based on different processes, or perhaps this might just be an effect that takes place under certain experimental conditions. Based on these studies, we might expect that, in our procedure, asking participants about the estimated moment of the cue (EMC), instead EMO, could affect our results. Indeed, we have no clear arguments to justify our testing the binding effect only in one direction while obviating the other one. Thus, we decided to test the binding effect in both directions as methodological caution. Given that Experiment 1A asked participants about EMO, in Experiment 1B we will test whether the temporal binding effect occurs if participants are asked for EMC instead of EMO.

This experiment was identical to Experiment 1A except that the information that we now presented at test was the actual moment of outcome (AMO), and therefore, the time that the participants were now asked to estimate was the EMC (see Table 1). The AMO was informed to take place at 16:54, and, like in Experiment 1A, it is important to note that participants did not receive any information about when any of the other filler events took place. Therefore, in this experiment they necessarily had to base the EMC only on the AMO.

Thus, the dependent variable was now computed as AMO minus EMC. Like in Experiment 1A, we hypothesized that the Causal group would estimate the target events as occurring closer in time to each other than the Non-Informed group, thus showing a causal binding effect, in this case when estimating the moment of the cue.

3.1. Participants

A total of 43 undergraduate psychology students from Deusto University participated in this experiment. As in Experiment 1A, the participants received course credit for their participation and the computer program randomly assigned them to one of two groups (i. e., 23 were assigned to the Causal group and 20 to the Non-Informed group). Using this sample size, a sensitivity analysis revealed a power of 0.80 to detect an effect of $d = 0.88$.

3.2. Results and discussion

As already mentioned, the dependent variable was calculated as the difference between the actual moment of the outcome and the estimated moment of the cue (AMO minus EMC) in minutes. Following the same criterion as in Experiment 1A, the data from one participant from the Causal group was now excluded from the analyses.

Panel B of Fig. 1 displays the results of this experiment. As can be seen in this figure, the participants of group Causal also estimated the target events as being closer to each other ($M = 363.50$, $SEM = 32.51$) than participants in the Non-Informed group ($M = 572.80$, $SEM = 81.46$). Like in Experiment 1A, a *t*-test analysis also revealed significant differences between groups in this experiment, $t(40) = 2.46$, $p = .018$, $ds = 0.76$. These results support those of Experiment 1A by showing that a causal binding effect can occur without direct experience with the events, both when estimating the outcome (Experiment 1A) and when estimating the cue (Experiment 1B).

In the following experiments, we aimed to replicate these results and to test some potential alternative interpretations of our findings.

4. Experiment 2A

The results of Experiments 1A and 1B could be due, as we hypothesized, to the fact that the Causal groups received the causal information and that the Non-Informed groups did not. However, it could be argued that in the Causal groups, the target events appeared twice: first, in the list of events that all participants read, and second, in the sentence in which participants of the Causal groups received the information about the causal relationship between the two target events. In the Non-Informed groups, by contrast, these events appeared only once in the list of events. Thus, differences between groups in estimating the time elapsed between cue and outcome might not be due to the causal information *per se*, but to the repetition of the events experienced by Group Causal. This could have made the participants process the target events differently in the Causal group (e.g., giving more salience to these events), which could have affected the differences in time estimation. In the following experiments, we added a new group to control for this possibility.

Therefore, in Experiments 2A and 2B, we try to replicate Experiments 1A and 1B but added a new group in each experiment (Non-Causal groups). In these groups, participants were explicitly informed about the non-causal relationship between the target events. If, as we hypothesize, knowledge of causal information was responsible for the differences in time estimation between groups Causal and Non-Informed in the previous experiments, then these differences should also be observed in the present experiments between groups Causal and Non-Causal, in addition to the differences that should be replicated between groups Causal and Non-Informed. In contrast, if the results of Experiments 1A and 1B were an artifact produced by the repetition of the target events in the Causal groups, then we should here reproduce the result observed between groups Causal and Non-Informed, but not between groups Causal and Non-Causal. As in Experiment 1A and 1B, the only difference between Experiment 2A and 2B was what the participants were asked to estimate on the test. In Experiment 2A, participants estimated the EMO; therefore, we showed them the AMC as a reference at test. Conversely, in Experiment 2B, we showed them the AMO at test, and they judged the EMC.

Before conducting Experiment 1A and 1B we did not conduct any power analysis to estimate sample size. A *post hoc* analysis revealed that the power of these experiments might not be sufficiently strong (0.73 and 0.67 for Experiments 1A and 1B, respectively). We are aware of the methodological concerns that this implies. For this reason, we conducted a power analysis for Experiment 2 using G*Power. For an effect size between Causal and Non-Informed as found in Experiments 1A and 1B (*Cohen ds* 0.66 and 0.76 respectively), and a target power of 0.95, a sample of 252 participants was required. To facilitate the recruitment of participants and to replicate the effect found in Experiments 1A and 1B using different samples, Experiments 2A and 2B were conducted via the Internet. Therefore, the experiments were accessible online until at least 252 participants were recruited.

4.1. Method

4.1.1. Participants

For Experiment 2A, we recruited 301 anonymous volunteers through the Internet, and they were randomly assigned to one of three groups. Nine of them were excluded from the analysis according to the same criteria as in the previous experiments. The remaining sample was composed of 117 participants in the Causal group, 96 in the Non-Causal group, and 79 in the Non-Informed group.

4.1.2. Procedure and design

The procedure was the same as Experiments 1A and 1B for groups Causal and Non-Informed. Participants in the Non-Causal groups were exposed to the same list of events. However, they were explicitly informed that there was non-causal relationship between the two target events (see Appendix A). As in the Causal group, this information about causality appeared immediately after participants had read the complete list of events and before the test screen was presented. Thus, we tried to create the exact conditions in the Causal

and Non-Causal groups. The only possible difference between them was that one group was told that the relationship was causal and the other group was told that it was not causal. As previously mentioned, participants in Experiment 2A judged the EMO. A summary of this design is shown in Table 1.

4.2. Results and discussion

Panel C of Fig. 1 shows the results of Experiment 2A. As in Experiment 1A the dependent variable was calculated as the difference between the AMC and EMO. Visual inspection of this figure shows that, as expected, participants in the Causal group estimated the target events as if they occurred closer in time to each other ($M = 318.15$, $SEM = 21.80$) than participants in the Non-Causal group ($M = 366.80$, $SEM = 29.15$) and the Non-Informed group ($M = 378.90$, $SEM = 23.20$). However, an analysis of variance (ANOVA) revealed no statistically significant differences between groups, $F(2,289) = 1.70$, $p = .184$, $\eta^2 = 0.01$.

5. Experiment 2B

As mentioned, the aim of Experiment 2B is to replicate the results of Experiment 1B using a second control group, Non-Causal, in which participants are explicitly informed about the non-causal relationship between the target events. We hypothesize that those participants that are verbally informed about the causal relationship between target events (Causal group) will estimate them closer in time than those that did not receive this information (Non-Informed group) and those who were informed about the non-causal relation (Non-Causal group).

5.1. Method

5.1.1. Participants

For Experiment 2B, 330 anonymous volunteers were recruited online and were randomly assigned to each of the three groups. Again, five of them were excluded from the analysis according to the same criteria as in the previous experiments. This resulted in 120, 101, and 104 participants in groups Causal, Non-Causal, and Non-Informed respectively.

5.1.2. Procedure and design

The procedure of this experiment was the same as used in Experiment 2A with the only exception that participants judged the EMC instead of the EMO (see Table 1). For this, at test we showed the AMO as a reference to participants.

5.2. Results and discussion

Results of Experiment 2B are shown in Panel D of Fig. 1. As in Experiment 1B the dependent variable was calculated as the difference between the EMC and AMO. As expected, participants in the Causal group estimated the target events as occurring closer to each other ($M = 353.00$, $SEM = 15.43$) than participants in the Non-Causal group ($M = 448.31$, $SEM = 27.05$) and in the Non-Informed group ($M = 427.91$, $SEM = 19.36$). Moreover, and unlike in Experiment 2A, the one way ANOVA revealed significant differences between groups, $F(2,322) = 6.08$, $p = .002$, $\eta^2 = 0.04$. *Post hoc t*-tests revealed statistically significant differences between the Causal and Non-Informed groups, $t(222) = 3.03$, $p = .003$, $ds = 0.40$, which replicate the results found in Experiment 1B. Interestingly, the analyses also showed a significant difference between the Causal and Non-Causal groups, $t(219) = 3.16$, $p = .002$, $ds = 0.42$, but not between the Non-Causal and Non-Informed groups, $t(203) = 0.61$, $p = .542$, $ds = 0.08$. Thus, the causal information results in the target events being estimated as closer to each other in the Causal group. The binding effect occurs when the events are described as causally related, not because they were presented once to one group and twice to the other two groups.

Taken together, the results of this experiment suggest that causal information affects time estimation. When participants estimate the moment of occurrence of the cue, then their judgement appears to be affected by causal information. However, when they estimate the moment of the outcome, the results are less clear.

Statistical comparisons between Experiments 1A and 1B or between Experiment 2A and 2B would not be appropriate, as these were conducted at different times and were not designed to test this comparison. However, it seems relevant to explicitly test whether causal information affects the participants' estimations differently according to whether they are required to estimate the moment of the cue or the moment of the outcome. In addition, some studies suggest that when using Libet's clock paradigm, action-binding and effect-binding could rely on different neural mechanisms (e.g., Wolpe et al., 2013). To this end, in Experiment 3 we used four different groups in which we manipulated two factors in a 2x2 design: The information that participants received (Causal vs. Non-Informed) and the event that participants judged at test (Cue vs. Outcome). Because the Non-Causal and Non-Informed groups appeared to work equivalently and because the Non-Informed control condition seemed more neutral, we only used this latter control in Experiment 3.

6. Experiment 3

In the previous experiments, our main manipulation was to verbally inform participants in the Causal groups about a causal relationship between the two target events. In contrast, participants in the other groups were not given such information. The results suggest that receiving verbal causal information made the participants estimate the two target events as occurring closer to each other, compared to participants who either did not receive any information or were explicitly told that the events were not causally related.

Our cover story was designed so that the cue event consisted, in all cases, of the technician feeding the animals. The outcome event was, in all cases, extreme hyperactivity in the animals. It could be argued that the participants' responses in the Causal groups could have been influenced by their pre-existing knowledge about the time it may take for a substance to affect behavior (see Buehner & May, 2002; Einhorn & Hogarth, 1986). If this were the case, the closer estimations of the target events in the Causal groups might not be due to the causal information itself, but to this prior knowledge. In order to rule out this alternative explanation, in Experiment 3, we defined the cue event in all groups as a nonsense alpha-numeric code (see Appendix A) instead of feeding the animals, so that participants could not have any previous expectations about how this event could affect behavior.

In addition, the results of experiment 2A and 2B suggest that there might be a difference between testing on EMO and testing on EMC. Thus, in order to compare these conditions, in Experiment 3, both conditions (EMO vs EMC) will be carried out in the same experiment.

6.1. Method

6.1.1. Participants

As in Experiments 2A and 2B, Experiment 3 was accessible through the Internet until we had recruited the minimum number of 252 participants needed to obtain 0.95 power, as already described for Experiment 2. Three hundred and twenty-five anonymous volunteers were recruited online for this experiment and were randomly assigned to one of four groups. Fourteen of them were excluded from the analysis according to the same criteria as in the previous experiments. This resulted in 63, 82, 90, and 76 participants in groups Causal Outcome, Non-Informed Outcome, Causal Cue, and Non-Informed Cue, respectively.

6.1.2. Procedure and design

The task was identical to the one used in the previous experiments, with the only difference that the cue event, which was feeding the animals in Experiments 1A-2B, was now replaced by the nonsense alpha-numeric code GIoP98JKKXONiOM. The outcome event (the animals' hyperactivity), the other (filler) events, and the order of presentation of the events within the list were the same as in the previous experiments.

As mentioned, we used a factorial 2x2 design. The two variables were (a) the information that we gave participants before the test: Causal information vs. Non-Informed, and (b) whether we asked participants about the EMC or EMO at test. As in the previous experiments, participants in the two Causal groups were informed just before testing that there was a causal relationship between the cue and outcome events, whereas the Non-Informed groups were not. Orthogonally, participants in the Cue groups were asked about the EMC on test, whereas Outcome groups were asked about the EMO. A summary of this design is shown in Table 1.

6.2. Results and discussion

The results of Experiment 3 are displayed in Panel E of Fig. 1. Visual inspection of this figure shows that, as in the previous experiments, participants in the Causal groups estimated the target events as occurring closer together than participants in the Non-Informed groups. This was true for both the Outcome groups: Causal Outcome ($M = 174.48$, $SEM = 31.35$) vs. Non-Informed Outcome ($M = 295.07$, $SEM = 35.32$) and for the Cue groups: Causal Cue ($M = 337.89$, $SEM = 38.02$) vs. Non-Informed Cue ($M = 473.95$, $SEM = 52.03$). A 2 (information: Causal vs. Non-Informed) $\times$ 2 (test: Outcome vs. Cue) ANOVA revealed a main effect of information, $F(1,307) = 7.16$, $p = .007$, $\eta^2 = 0.03$, which replicates the effect found in previous experiments, a main effect of test, $F(1,307) = 16.96$, $p < .001$, $\eta^2 = 0.052$, and no interaction between these variables $F(1,307) = 0.034$, $p = .852$, $\eta^2 < 0.001$. *Post hoc t*-tests confirmed these observed differences, both between Outcome groups, $t(143) = 2.41$, $p = .017$, $ds = 0.40$, and between Cue groups, $t(164) = 2.12$, $p = .035$, $ds = 0.33$. Finally, a *t*-test also revealed differences between the two Causal groups, $t(151) = 3.05$, $p = .002$, $ds = 0.50$, and between the two Non-Informed Groups, $t(156) = 2.83$, $p = .005$, $ds = 0.45$. These results suggest that, as in the previous experiments, verbal causal information can induce a binding effect, that is, a closer estimated time between the occurrence of the cue and the outcome when these events are described as causally linked. Also, results of this experiment show that this effect is not merely due to prior knowledge about the time that food may take to affect behavior, because in this experiment the potential cause was described as a nonsense alphanumeric code. The results also indicate differences in whether participants estimate the EMO or EMC at test.

7. Experiment 4

In four of the five previous experiments (i.e., 1A, 1B, 2B, and 3), causal binding was observed in the Causal groups, that is, when participants were informed that there was a causal relationship between the cue and the outcome. This binding effect did not occur in the control groups, when participants were not informed about the relationship between the target events (Experiments 1A, 1B, 2B, and 3) or when they were explicitly informed that the events were not causally related (Experiment 2B). Moreover, the effect occurred regardless of whether the potential cause was feeding the animals (Experiments 1A, 1B, and 2B) or a nonsense alphanumeric code (Experiment 3), which suggests that the observed binding effect was not due to previous knowledge about the potential cause and the time it takes to produce its effects. Finally, causal binding was observed in all cases in which the participants were asked to estimate the EMC (Experiments 1B, 2B, and 3), but was not as robust when participants were asked to estimate the EMO, as the binding effect was observed in Experiments 1A and 3, but not in Experiment 2A.

The results of Experiment 2A showed no significant differences between any of the three groups (Causal, Non-Informed, and Non-

Causal). This unexpected absence of differences may suggest that the temporal binding effect can only occur when participants are asked about EMC (as in Experiments 1B, 2B and 3). However, both Experiment 1A and Experiment 3 showed differences between the Causal and Non-Informed groups when participants were asked to estimate the EMO. Thus, the absence of differences in Experiment 2A could probably be a false negative.

Thus, we designed one more experiment in order to provide replications of the results that we already observed and test those conditions that we might be lacking in the previous experiments. As shown in Table 1, in Experiment 4 we use an alphanumeric code as the potential cause (as in Experiment 3) to ensure that the results are not due to previous knowledge about the feeding cause used in Experiments 1 and 2. In addition, we will test Causal vs. Non-Causal groups (rather than Non-Informed groups which had already been tested in almost all our previous experiments). Orthogonally, we will ask participants about EMC or EMO. Results will show if, as the results of Experiment 2A suggest, no temporal binding is obtained under these conditions when asking about EMO, or whether, if we might observe binding even in these conditions, the null effect observed in Experiment 2A could be a false negative.

7.1. Method

7.1.1. Participants

One hundred and seventy psychology students from the Universidad Autónoma de Madrid took part in this experiment. Following the data selection criteria described above, data from 8 of these participants were excluded from the analyses. The total sample was composed of 43, 46, 40, and 33 participants in groups Causal Outcome, Non-Causal Outcome, Causal Cue, and Non-Causal Cue, respectively. Of the total sample, 150 (88.23%) self-identified as female, 19 as male, and 1 as other. The mean age was 19.46 years old (max 36, min 18).

7.1.2. Procedure and design

The task used was identical to the one used in the previous experiments. Four groups were programmed, two of them receiving causal information and two receiving non-causal information, as in Experiment 2. Orthogonally, two of them were asked to judge the EMO and two of them the EMC. In all cases the potential cause (and the explicitly non-causal event) was the nonsense alphanumeric code used in Experiment 3 (see Table 1 for a comparative summary of the design and critical features of all six experiments).

7.2. Results and discussion

The Panel F of Fig. 1 shows the results of Experiment 4. As can be seen in this figure, the groups receiving causal information, that is, groups Causal Outcome and Causal Cue, estimated the target events closer ($M = 292.05$, $SEM = 31.86$ and $M = 337.72$, $SEM = 26.96$ respectively) than groups receiving non-causal information, that is, groups Non-Causal Outcome and Non-Causal Cue ($M = 456.37$, $SEM = 53.27$ and $M = 543.30$, $SEM = 67.76$ respectively). A 2 (information: Causal vs. Non-Causal) $\times$ 2 (test: EMC vs. EMO) ANOVA revealed a main effect of information, $F(1,158) = 14.40$, $p < .001$, $\eta^2 = 0.08$, but not a main effect of test, $F(1,158) = 1.91$, $p = .168$, $\eta^2 = 0.01$, or interaction, $F(1,158) = 0.189$, $p = 0.66$, $\eta^2 = 0.001$. *T*-test also revealed differences between the two Outcome groups, $t(87) = 2.57$, $p = .012$, $ds = 0.54$, and between the two Cue groups, $t(71) = 2.95$, $p = .004$, $ds = 0.69$, as a function of whether they were informed about a causal or a non-causal relationship between the target events. Thus, these results support the findings of the previous experiments showing that temporal binding occurs in the groups informed about a causal relationship also when the potential cause is an alphanumeric code for which participants could have no previous knowledge (as in Experiment 3). In addition, binding was also observed when the control group was informed about a non-causal relationship between the target events (as in Experiment 2B). Our results also show that the effect, at least under our experimental conditions, occurs both when participants are asked to estimate the EMO and the EMC (as in Experiments 1A, 1B, 2B, and 3), suggesting that the null result of Experiment 2A was probably a false negative.

8. General discussion

In recent years, several studies have confirmed the effect of a causal relationship between two events by estimating the time elapsed between them. These studies show that when two events are causally related, participants estimate that they occur closer together in time than when they are not causally related. This effect has been termed *causal binding* (Buehner & Humphreys, 2009; Buehner, 2012, 2015), and it has been studied using several procedures. However, all these procedures are based on paradigms that, through experiencing successive presentations of physical stimuli (e.g., pressing the space bar and hearing a tone), participants infer the causality between the events (or not). In five of the six experiments presented here, we show a causal binding effect using a novel procedure that differs from traditional paradigms in several aspects. First, participants have no direct experience with the physical events they have to judge or with the time elapsed between them; instead, they are verbally informed about the events and the time at which one of the events occurred. Second, participants do not infer causality from the task, but they are informed about it. Finally, the information is not presented in a trial-by-trial format, but in one simple sentence.

Using this paradigm, Experiments 1A and 1B showed that the participants informed about the causal relationship between the two events estimated the cue and the outcome as occurring temporally closer together than Non-Informed participants. Experiments 2B, 3, and 4 replicated the results of Experiments 1A and 1B and explored alternative explanations for these findings. Experiments 2B and 4 suggest that the effects observed cannot be due to differences in the number of times participants read about the target events, as these experiments used control groups that were informed of a non-causal relationship between the events, so the events were presented the same number of times in these Non-Causal control groups as in the Causal groups. Finally, Experiments 3 and 4 show that the binding

effect observed cannot be explained by prior knowledge that participants could use to guide their time estimation, because these two experiments used simple alphanumerical codes as the potential (and hence, unknown) cause. In addition, binding effects were observed under these conditions in Experiments 1A, 1B, 2B, 3, and 4, regardless of whether participants were asked to estimate the moment of the cue (EMC) or the moment of the outcome (EMO).

Nonetheless, we found some unexpected results. In Experiment 2A, we observed a non-significant difference between Group Causal and Group Non-Causal, and between Group Causal and Group Non-Informed. Although these unexpected results may suggest that the binding effect does not occur when participants are asked to estimate the EMO (not the EMC as shown in Experiment 2B), these negative results were not found in Experiments 1A, 3, and 4, which also tested the EMO, so this suggests that the result of Experiment 2A was probably a false negative. Related to this point, we found a test effect in Experiment 3, not replicated in Experiment 4, indicating that participants asked about the moment of the outcome tended to judge both events as occurring closer together than those asked about the moment of the cue. This effect was not reproduced in Experiment 4. Therefore, we should not draw any conclusions from it.

Several researchers have suggested that participants' intentional action is needed to obtain a binding effect (e.g., Engbert, Wohlschläger, & Haggard, 2008; Haggard, Clark, & Kalogeras, 2002; Haggard & Clark, 2003; Tsakiris & Haggard, 2003). According to these authors, to compress the estimation of time elapsed between two events, the first event must be an intentional action of the participant, and the second event an external event caused by this action (e.g., a tone). Thus, participants will estimate their action and the second event as occurring closer together only when the first event is intentional. Thus, these authors call this effect *intentional binding* rather than causal binding. However, the results of other studies suggest that it is the perception of causality between the two events that is responsible for the binding effect (e.g., Eagleman & Holcombe, 2002; Ruess et al., 2020; Blakey et al., 2019; Buehner & Humphreys, 2009; Moore et al., 2009; Strother et al., 2010).

Consequently, this effect has also been termed *causal binding*. According to this view, no intentional action is required; instead, binding effects are observed in situations where participants perceive a cause-effect relationship between two events. Although our experiments were not specifically designed to contrast the merits of these two theoretical accounts, the results observed in our experiments provide stronger support for the causal binding account. Indeed, participants did not conduct any intentional action in our experiments and still their time estimations were influenced by the causal relationships between the target events. However, it could be argued that our experiments do not fully rule out that human action and action intention are necessary for the binding effect because our results could be seen as an asynchronous type of observational binding (see Moore et al., 2013; Wohlschläger et al., 2003), or even as an embodiment effect (see Laroché et al., 2014) resulting in participants simulating the actions in their minds. In this case, one could conclude that a mental representation of an action (although not the action per se) might still be needed for the binding effect to occur. More studies are needed comparing the mental representation of human-generated causes, such as those used in our experiments, against the representation of non-causal events, and that of causes generated by other types of agents (e.g., natural causes without human action).

Beyond these two traditional explanations for the binding effect (i.e., causality vs. intentionality), other researchers have suggested that binding is caused by other, different processes. For example, several authors have proposed that binding is caused by a sensory integration mechanism (see, Klaffehn et al., 2021; Kirsch et al., 2019; Wolpe et al., 2013). Others suggest that cue and outcome binding may be generated by the activation of the learned cue-outcome association and the comparison between predicted and observed outcomes (Tanaka et al., 2019, see also Tonn et al., 2021). Other authors are even more critical, proposing that binding is caused, not by processes related to temporal estimation, but by severe methodological factors and artifacts. For example, Schwarz and Weller (2023) showed that binding effects can be at least partially explained by an attentional artifact (see also Gutzeit et al., 2023).

It is important to note that due to the many methodological differences between our paradigm and the one traditionally used to study temporal binding, the underlying mechanisms might be different. For example, the experience of physical events in traditional paradigms may involve perceptual and attentional processes related to the stimulus modality. However, our experimental procedure may involve judgmental processes that might be absent in some of the traditional binding experiments. Also, temporal estimation processes may be different when judging short time intervals (such as seconds in causal binding studies) or when the intervals are longer (minutes or hours, as they are supposed to be in our represented scenarios). In that case, the experiments previously described in the literature and the ones presented herein might not be comparable as they would deal with different, although convergent, effects. Our experiments do not allow us to conclude whether the processes underlying the effect that we observed are the same as the processes causing the binding effects in other paradigms, but they open the door to new and fascinating research avenues.

Among all the interpretations that have been proposed, perhaps the one that may be most pertinent to our research is the use of heuristics and the influence these may have on participants' temporal judgments (e.g., Reddy, 2022a, 2022b). According to this interpretation, in ambiguous situations or in the face of fuzzy temporal judgments (as implemented in our experiments), participants' responses will be more influenced by the use of heuristics (e.g., "causally linked events are usually closer together in time") than by perceptions of time per se. This interpretation could explain not only the results of our current experiments, but also many of the results of the studies published to date on temporal binding (see Reddy, 2022a, 2022b). Although our experiments were not designed to test the heuristics' hypothesis, they do provide support for this hypothesis as compared to more traditional ones, because what our results show is that binding can occur in the absence of direct experience with the target events, and in the absence of direct experience with causal and temporal information. In fact, our experiments extend this theoretical account by showing that heuristics could affect the participants' judgments not only in laboratory experiments in which participants experience the information on a trial by trial basis, as is usually the case, but also in more ecological settings in which participants acquire information through verbal information.

In our view, almost all the paradigms previously used to study causal binding present certain ecological problems that reduce the generalization of this effect and its applicability to real-life situations. First, in most studies, participants have to estimate very short

lapses of time that range from 100 ms (Ebert & Wegner, 2010; Moore & Haggard, 2008; Moore et al., 2009) to a few seconds (Buehner & Humphreys, 2009; Humphreys & Buehner, 2009), whereas there are many situations in daily life in which the time lapses that people need to estimate are much longer. In addition, the very nature of the tasks used in previous experiments (e.g., pressing a key followed by the occurrence of a tone) is barely comparable to most real-life situations in which people must estimate the time between events. Finally, in many situations in our daily lives, we infer causality from verbal information rather than directly experiencing the stimuli over the course of several trials. For all these reasons, we believe that the experimental paradigm we used in these six experiments is more ecological than those previously used and helps apply temporal binding research to real-life situations.

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CRedit authorship contribution statement

Carmelo P. Cubillas: Conceptualization, Methodology, Data curation, Formal analysis, Software, Writing – original draft.
Helena Matute: Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are openly available on the Open Science Framework at <https://osf.io/bg672/>.

Appendix A

List of events presented to participants in each group, for each of the six experiments. Each event was presented on a different screen. Original lists were presented in Spanish.

Event	Exp.	Group	Text
1	All	All	<i>Jon is a technician in a laboratory that experiments with guinea pigs. Among other tasks, his job consists of feeding them, keeping the experimentation instruments clean, and taking note of any incident that occurs in the laboratory.</i>
2	All	All	<i>Now you will see Jon's activities last Monday and the time that he spent doing each one.</i>
3	All	All	<i>Enters main building door.</i>
4	1A, 1B, 2A, 2B	All	<i>Feeds new guinea pigs (genetically modified strain) with 300 g. willow leaf pills - (10 mins.)</i>
	3, 4	All	<i>Task GIoP98JKKXONiOM - (10 mins.)</i>
5	All	All	<i>Clean the laboratory apparatus: racks, pipettes, and calorimeters - (102 mins.)</i>
6	All	All	<i>Organizing store - (102 min.)</i>
7	All	All	<i>Updating invoices - (18 min.)</i>
8	All	All	<i>Order materials to renovate the laboratory: calorimeter and stove - (12 min.)</i>
9	All	All	<i>Meeting with the boss and planning the work for the following weeks - (170 min.)</i>
10	All	All	<i>Review temperature and humidity in the animal facilities: 28 °C, 82% - (53 min.)</i>
11	All	All	<i>Cleaning guinea pig cubicles - (85 min.)</i>
12	All	All	<i>INCIDENT: WHILE HE WAS CLEANING THE CUBICLES OF THE GUINEA PIGS, THEY BEGAN TO RUN AND MOVE VERY QUICKLY IN THEIR CUBICLES. NEVER BEFORE HAVE THE GUINEA PIGS BEEN SEEN TO BE SO AGITATED AND NERVOUS.</i>
13	1A, 1B, 2A, 2B	Causal	<i>Later investigations have shown that in this strain of genetically modified guinea pigs, willow leaf intake caused an extreme activation of the sympathetic nervous system which causes a high level of motor activation in these animals.</i>
	2A, 2B	Non-Causal	<i>Later investigations have shown that in this strain of genetically modified guinea pigs, willow leaf intake DID NOT cause an extreme activation of the sympathetic nervous system which causes a high level of motor activation in these animals.</i>

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Event	Exp.	Group	Text
	3, 4	Causal Outcome Causal Cue	Later investigations have shown that in this strain of genetically modified guinea pigs a task carried out by the technician caused the high level of activation showed by the guinea pigs. Specifically, it was the task coded GloP98JKKXONiOM which caused the guinea pig's activation.
	4	Non-Causal Outcome Non-Causal Cue	Later investigations have shown that in this strain of genetically modified guinea pigs, the task coded GloP98JKKXONiOM DID NOT cause an extreme activation of the sympathetic nervous system, which causes a high level of motor activation in these animals.
14	1A, 2A	All	To create a laboratory report, it is important to establish when some events in the laboratory happened. Your job is to estimate when the guinea pigs began to run and move very quickly in their cubicles. To help you, we will give you the only specific time that we know, along with the activity that Jon was performing at that particular time. 08:32 Fed the new guinea pigs (genetically modified strain) with 300 g. of willow leaf pills - (10 mins.) When did the guinea pig begin to run and move very quickly?
	1B, 2B	All	To create a laboratory report, it is important to establish when some events happened in the laboratory. Your job is to estimate when Jon fed the new strain of genetically modified guinea pigs with 300 g. of willow leaf pills. To help you, we will give you the only specific time that we know, along with the activity that Jon was performing at that particular time. 16:54 INCIDENT: WHILE HE WAS CLEANING THE CUBICLES OF THE GUINEA PIGS, THEY BEGAN TO RUN AND MOVE VERY QUICKLY IN THEIR CUBICLES. NEVER BEFORE HAVE THE GUINEA PIGS BEEN SEEN TO BE SO AGITATED AND NERVOUS. When were the guinea pigs fed?
	3, 4	Causal Cue Non-Informed Cue Non-Causal Cue	To create a laboratory report, it is important to know when certain events happened in the laboratory. Your job is to estimate at which time Jon performed the task GloP98JKKXONiOM. To help you, we will give you the specific time at which it was known that Jon was carrying out the activity 16:54 INCIDENT: WHILE HE WAS CLEANING THE CUBICLES OF THE GUINEA PIGS, THEY BEGAN TO RUN AND MOVE VERY QUICKLY IN THEIR CUBICLES. NEVER BEFORE HAVE THE GUINEA PIGS BEEN SEEN TO BE SO AGITATED AND NERVOUS. When did Jon perform the task GloP98JKKXONiOM?
	3, 4	Causal Outcome Non-Informed Outcome Non-Causal Outcome	To create a laboratory report, it is important to know when certain events happened in the laboratory. Your job is to estimate when the guinea pigs began to run and move very quickly in their cubicles. To help you, we will give you the specific time at which it was known that Jon was carrying out the activity. 08:32 Task GloP98JKKXONiOM- (10 mins.) When did the guinea pigs begin to run and move very quickly?

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