**Explicit and implicit timing in healthy and pathological aging:
Disentangling the role of age and cognitive functioning in temporal processing**

Mariagrazia Capizzi^{1*}, Antonino Visalli^{2*}, Alessio Faralli³, & Giovanna Mioni⁴

¹Université Paul Valéry Montpellier 3, EPSYLON EA 4556, F34000, Montpellier, France

²Department of Neuroscience, University of Padova, 35128, Padova, Italy

³Department of Neuroscience, Psychology, Drug Research, and Child Health (NEUROFARBA),
University of Florence, Florence, Italy

⁴Department of General Psychology, University of Padova, 35131, Padova, Italy

* First author equal contribution

Corresponding authors:

Giovanna Mioni

Department of General Psychology

University of Padova

giovanna.mioni@unipd.it

Mariagrazia Capizzi

Université Paul Valéry

Montpellier

mgcapizzi@ugr.es

Abstract

This study aimed to test two common explanations for the general finding of age-related changes in temporal processing. The first one is that older adults have a real difficulty in processing temporal information as compared to younger adults. The second one is that older adults perform poorly on timing tasks because of their reduced cognitive functioning. These explanations have been mostly contrasted in *explicit* timing tasks, where participants are overtly informed about the temporal nature of the task. Fewer studies have instead focused on age-related differences in *implicit* timing tasks, where no explicit instructions to process time are provided. Moreover, the comparison of both explicit and implicit timing in older adults has been restricted to healthy aging only. Here, a large sample (N= 85) of healthy and pathological older participants completed explicit (time bisection) and implicit (foreperiod) timing tasks. Participants' age and general cognitive functioning, measured with the Mini-Mental State Examination (MMSE), were used as continuous variables to explain performance on explicit and implicit timing tasks. Results showed a clear dissociation between the effects of healthy cognitive aging and pathological cognitive decline on processing of explicit and implicit timing. Whereas age and cognitive decline similarly impaired the non-temporal cognitive processes (e.g., memory for and/or attention to durations) involved in explicit temporal judgements, processing of implicit timing survived normal age-related changes. These findings carry important theoretical and practical implications by providing the first experimental evidence that processing of implicit, but not explicit, timing is differentially affected in healthy and pathological aging.

Keywords: explicit timing; implicit timing; aging; time bisection task; foreperiod

Introduction

Age-related changes in temporal processing are commonly reported (Droit-Volet, 2016; Friedman & Janssen, 2010; Janssen, Naka, & Friedman, 2013; Lamotte & Droit-Volet, 2017; Maaß,

Wolbers, van Rijn, & Riemer, 2021; Wearden, 2005; Wittmann & Lehnhoff, 2005). Because temporal judgements also demand cognitive resources such as attention and working memory, it is debated whether these changes can be genuinely attributed to a slowing down of temporal information processing with aging or should be rather considered as a side effect of the reduced cognitive functioning of older adults (Baudouin, Isingrini, & Vanneste, 2018; Mioni, Capizzi, & Stablum, 2020). Support for the latter hypothesis also comes from studies of pathological aged populations such as patients with Alzheimer's disease (AD). Relative to age-matched controls, AD patients – who are known to present severe cognitive deficits (Albert et al., 2011; Alzheimer's Association, 2014) – perform poorly on timing tasks (see El Haj & Kapogiannis, 2016; Mioni, Román-Caballero, Clerici & Capizzi, 2021, for reviews). As will become clear below, the main goal of the present study was to disentangle the role of healthy cognitive aging and pathological cognitive decline in explicit and implicit timing.

Research on temporal processing in older adults mainly relies on *explicit* timing tasks. The term explicit indicates that participants are overtly informed about the temporal nature of the task (Coull & Nobre, 2008). For example, in the time bisection task (the one also used in the present study and illustrated in Figure 1, A), participants are first familiarized with a “short standard” and a “long standard” duration and then instructed to classify intermediate durations as being more similar to the short or the long standard (Kopce & Brody, 2010; Penney & Cheng, 2018). These explicit task requirements entail paying attention to time in order to store in memory the short and long standard durations for later comparison with the intermediate presented durations. Such psychological operations are typically explained within the framework of pacemaker-based accounts of time perception (e.g., Gibbon, Church, & Meck, 1984; Treisman, 1963). According to these influential models, temporal judgments are assumed to depend on a single internal clock, described as a pacemaker–counter device also including memory and decision stages. In its simplest form, the pacemaker would emit pulses that are accumulated in a counter and the number of pulses counted determines the perceived duration of an interval: the greater the number of pulses, the

longer the estimation of the interval duration. The pulses stored into the accumulator are then transferred to working memory (i.e., memory stage); an additional decision stage would finally compare the pulses accumulated in working memory to those already stored in a reference memory system to identify an appropriate outcome. Applied to the time bisection task, these models propose that participants would decide whether a presented duration is short or long by comparing the number of pulses accumulated in working memory with the number of pulses stored for the short and long standard durations in reference memory (Lustig & Meck, 2001). Figure 1, B illustrates the behavioural patterns that can be observed in the time bisection task as function of both ideal and possible age-related performance.

Figure 1. (A) Schematic view of the explicit (time bisection) task. In a first training phase, participants memorized a “short standard” (480 ms) and a “long standard” duration (1920 ms). During a

subsequent testing phase, they indicated whether the interval duration elapsing from the onset of the thicker circle to the onset of the cross was closer to the previously memorized “short standard” or “long standard”. Responses were given by pressing two response keys on the computer keyboard. I.T.I. stands for Inter-Trial-Interval. **(B) Patterns of behavioural performance in the time bisection task.** A common way of looking at performance on the time bisection task is to construct a psychometric function by plotting the proportion of trials in which participants respond “long” as a function of interval duration. The black psychometric function depicts an ideal performance in which participants never respond “long” to the short standard duration, whereas they always respond “long” to the long standard. At the intermediate duration (1200 ms), they are equally likely to respond short or long. Relative to the reference, a shift of the psychometric function towards the left (light blue line) or the right (blue line) means over- or under-estimations, respectively. Conversely, a flatter psychometric function (pink line) is indicative of a poorer temporal performance (i.e., participants tend to respond “short” to long durations and “long” to short durations). Although it is difficult to completely isolate clock from memory and decision stages, it makes sense to hypothesise that age-related changes in clock speed should be mainly expressed by a leftward shift of the psychometric function (i.e., slower clock in older adults). By contrast, a flatter psychometric function in older adults could be likely attributed to a deficit in the additional cognitive processes (e.g., memory for and/or attention to durations) required to correctly perform on the time bisection task.

Explicit requirements to process time are absent in the context of *implicit* timing tasks. As illustration, consider a warned reaction time (RT) task just entailing a fast response to a target stimulus, like the task used here and depicted in Figure 2, A. The time interval between the warning signal (thicker circle) and the target (cross symbol), otherwise known as “foreperiod”, could assume one of different durations with equal a-priori probability at the beginning of a trial. In this kind of tasks, the probability that the target will occur at the longest foreperiods grows up with the passage of time, as formally described by the hazard function, i.e., the conditional probability that an event will occur given it has not yet occurred (Herbst, Fiedler, & Obleser, 2018; Janssen & Shadlen, 2005; Visalli, Capizzi, Ambrosini, Mazzonetto, & Vallesi, 2019; see Figure 2, B, for an illustration

of the hazard rate). Participants are sensitive to the hazard function, a conclusion supported by their shorter RTs for the longer foreperiod trials, the so-called “variable foreperiod effect” (hereafter simply referred to as the foreperiod effect; Capizzi & Correa, 2018; Coull, 2009; Niemi & Näätänen, 1981; Nobre & van Ede, 2018), which is represented by the back line in Figure 2, B. The behavioural benefit afforded by elapsing time during longer foreperiod trials is interpreted as evidence for an implicit processing of time, since the foreperiod effect occurs even if participants are not explicitly instructed to pay attention to time or are uninformed about the used interval durations.

Figure 2. (A) Schematic view of the implicit (foreperiod) task. The foreperiod task comprised the same stimulus material and general procedure of the time bisection task, but differed in the specific task instructions given to participants. Specifically, the participants’ task was to press the space bar as quickly as possible whenever the cross appeared inside the circle. Thus, no instructions to memorize interval durations

were provided for the implicit timing task. The interval duration separating the thicker circle from the cross could randomly assume one of seven values with equal a-priori probability. I.T.I. stands for Inter-Trial-Interval. **(B) Patterns of behavioural performance in the foreperiod task.** Performance on the foreperiod task is plotted in terms of reaction time (RT) as function of interval duration (or foreperiod, FP). For illustrative purposes, the depicted log-RTs are in arbitrary units (a.u.). The black line shows the reference finding typically observed in the foreperiod task, with shorter RTs at longer interval durations (i.e., the foreperiod effect). The foreperiod effect is formally described by the hazard function (represented in grey), that is, the increasing conditional probability that an event will occur given it has not yet occurred. The size of the foreperiod effect is taken as evidence for an implicit processing of time, considering that participants are not explicitly instructed to memorize or use interval durations. Relative to the reference, the blue line depicts the presence of a generalized RT slowing that, however, does not imply a deficit in the processing of implicit timing, as indexed by the size of the foreperiod effect. By contrast, the light blue line depicts a smaller foreperiod effect, which is indicative of an impaired use of implicit timing (i.e., no benefit afforded by the passage of time). Assuming that implicit timing tasks rely less on cognitive resources than explicit timing tasks do leads to the prediction that processing of implicit timing should be spared in older adults as compared to processing of (more demanding) explicit timing (i.e., a pattern more consistent with the blue, rather than the light blue, line).

To our knowledge, the comparison of explicit and implicit timing has been thus far restricted to healthy aging only (Droit-Volet, Lorandi, & Coull, 2019). In a between-participants design, one group of older adults and one group of younger participants performed an explicit timing task (i.e., temporal generalization task), whereas different age groups were engaged in an implicit timing task (i.e., a variant of the foreperiod task; Piras & Coull, 2011; see also Gallego Hiroyasu & Yotsumoto, 2020, for evidence from explicit and implicit rhythmic temporal tasks). Participants' performance on explicit and implicit timing tasks were also related to cognitive scores derived from neuropsychological tests. Results showed that older adults were as accurate as younger participants in both explicit and implicit timing tasks; however, older participants were more variable than

younger ones in the explicit timing task and their performance was explained by lower attentional capacity rather than age. This finding, thus, suggests that performance of older participants on the explicit timing task did not reflect a timing deficit per se, but was rather a consequence of their lower attentional abilities. By contrast, age-related differences in the implicit timing task were explained exclusively by age rather than cognitive scores.

Collectively, the findings by Droit-Volet and colleagues (2019) speak to a different involvement of age and cognitive functioning in explicit and implicit timing tasks. Although interesting, the approach of that study was based on a correlational analysis, in which performance of healthy older adults was related to neuropsychological scores. A more direct way to disentangle the contribution of age and cognitive resources to processing of explicit and implicit timing is to include both healthy and pathological aged samples and to use participants' age and level of cognitive decline as continuous predictors of performance. Towards this end, we devised a within-participants design where, for the first time, healthy and pathological aged populations, such as AD patients and individuals with Mild Cognitive Impairment (MCI), completed (explicit) time bisection and (implicit) foreperiod tasks. Participants' cognitive functioning was measured with the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975), one of the most popular screening tools in clinical practice.

Different, not mutually exclusive, predictions are equally plausible. As concerns explicit timing, a first prediction is that if age-related differences in the time bisection task are due to a slowing down of the clock with aging, this should be reflected by a leftward shift of the psychometric function that is better explained by the age predictor rather than the MMSE one. If, conversely, age-related changes depend on the reduced cognitive functioning of older participants, participants' performance should be characterized by a flattening of the psychometric function, which is explained by MMSE scores rather than age. Concerning implicit timing, performance on the less demanding foreperiod task should be unrelated to the cognitive functioning of older participants and better explained by age (e.g., Droit-Volet et al., 2019).

Method

Participants

Ninety-one older adults recruited from different centres in the Italian territory voluntarily took part in the study. Six participants were excluded as they just completed the implicit timing task, thus, leaving a final sample of 85 older adults. Twenty-three participants resided in the municipality of Padova: 14 were tested at their home and 9 at local social centres. Thirteen participants resided in the municipality of Sacile (Pordenone) and tested at local social centres. Fifteen participants resided in the municipality of Vicenza and tested at local social centres. Twenty-one participants resided in the municipality of Grosseto and were tested either at home (N=14) or at a local social centre (N=7). Finally, 13 resided in the municipality of Cagliari and all were tested at home. To control for differences in the testing context (home vs. public centres), particular attention was given to the experimental setting such that all the participants performed the temporal tasks in a quiet and normally illuminated room and all of them received the same instructions. Participants' cognitive functioning was defined according to the score (corrected for age and education) obtained on the Italian version of the Mini-Mental State Examination (MMSE; Folstein et al., 1975; for the Italian version, Magni, Binetti, Bianchetti, Rozzini, & Trabucchi, 1996). Of note, although we considered the scores obtained in the MMSE as a continuous variable in the below analyses, for completeness Supplementary table S1 also reports the clinical classifications (i.e., dementia and Mild Cognitive Impairment) of our sample as commonly done in the literature, along with the demographic characteristics of the participants included in the study.

All the participants had normal or corrected-to-normal vision and normal hearing. All of them signed an informed consent before participation, in accordance with the Declaration of Helsinki. The experiment was approved by the Ethics Committee of the Department of General Psychology of the University of Padova (protocol n. 3387).

Procedure and Task

Participants were seated in a quiet room at an approximate distance of 60 cm from the computer screen (15.6") that produced and recorded experimental events via Psycophy Software (Peirce, 2008). Explicit and implicit timing tasks comprised the same stimulus material and general procedure but differed in the specific task instructions given to participants (Figure 1, A and Figure 2, A). For both tasks, stimuli consisted of a grey circle and a grey cross presented at the centre of a lighter grey background screen. A thin circle was initially displayed for 500 ms (Inter-Trial-Interval, ITI), followed by a thicker circle that could assume one of the following interval durations: 480, 720, 960, 1200, 1440, 1680, or 1920 ms. After the duration had elapsed, a cross appeared in the centre of the circle for 500 ms. For the *explicit timing task*, the experimental session started with a training phase, in which participants were asked to memorize two standard durations: 480 (short standard) and 1920 ms (long standard), each presented 10 times. During a subsequent testing phase, participants were instructed to indicate whether the temporal interval elapsing from the onset of the thicker circle to the onset of the cross was closer in duration to the previously memorized "short standard" or "long standard". Responses were given by pressing two response keys ("S" and "L" on the computer keyboard), which were covered with labels "B" and "L" (i.e., "Breve" and "Lungo", respectively, meaning short and long in Italian); response keys were counterbalanced between participants.

In the *implicit timing task*, participants were instructed to press the spacebar as fast as possible whenever the cross appeared in the centre of the thicker circle, as commonly done in a variable foreperiod task.

For both explicit and implicit timing tasks, no information about stimulus durations was given to participants. The experiment consisted of a total of 6 blocks (3 blocks for each timing task) of 42 trials each (6 repetitions for each temporal interval). Forty-four participants started with the explicit timing task, whereas 41 participants started with the implicit timing task. Explicit and

implicit timing tasks were separated by a short break to allow participants a brief rest before undergoing the second task.

Statistical Analyses

The same statistical approach was applied to the analysis of both explicit and implicit timing tasks by means of Mixed-Effects models, which were implemented in the R environment (<http://www.R-project.org/>) using functions from the *lme4* library (Bates, Kliegl, Vasishth, & Baayen, 2015). Concerning the explicit timing task, the probability of “long” responses was modelled through logistic regressions conducted with the *glmer* function (i.e., a generalized linear mixed model, GLMM, with probit-link function). For the implicit timing task, linear regressions were conducted on log-transformed reaction times (RTs) by using the *lmer* function (i.e., a linear mixed model, LMM). For both tasks, a full GLMM/LMM was specified including “Interval duration”, “MMSE score”, “Age” variables and their interactions as fixed terms. These continuous variables were centred and scaled to improve their interpretation and the fit of the model. Participants were treated as random effects.

To quantify and evaluate the contribution of MMSE scores and Age in explaining the data, two model comparisons (as implemented in the *lme4* function *anova*) were conducted, each one including three models: (i) a simple model with just Interval duration as fixed term; (ii) a model adding in one case MMSE scores and in the other case Age (and their interaction with Interval duration); and (iii) the full model including Interval duration and both MMSE score and Age variables.

Analyses were conducted on data from all the participants (N= 85) with no exclusion criteria. However, to check for the robustness of our results, we also repeated the above-mentioned analyses by excluding participants according to the proportion of trials in which they did not provide a response (see the Supplementary material). Specifically, for each participant and separately for each task, we calculated the proportion of non-given responses. Then, the highest

proportion of non-given responses between tasks was taken for each participant and analyses were repeated four times including participants with a proportion of non-given responses lower than .1, .2, .3, or .4, respectively. Overall, these control analyses confirmed the robustness of our main findings (see Supplementary Tables S2-3).

Results

Explicit timing task. Model comparison (Table 2) showed that the best fitting model was the full model including Interval duration, MMSE and Age variables (a summary of the model output is presented in Table 3). Figure 3 shows the finding of significant interactions between Interval duration and MMSE and between Interval duration and Age. Specifically, the shape of the psychometric function became flatter with lower MMSE scores and increased age. Main effects of MMSE and Age, which indicate differences at the middle interval duration, were not significant, implying that there were no systematic changes in temporal judgements (i.e., over- or under-estimation) modulated by MMSE or Age.

Table 2. Model comparison for the explicit and implicit timing tasks showed that the best fitting model was the full model including the Interval duration and both the MMSE score and Age variables.

Fixed effects	log-likelihood	χ^2 (df)	$p(>\chi^2)$	AIC
<i>Explicit timing task (a)</i>				
Interval duration	-8262.7			16531
Interval duration $\times$ MMSE	-8166.9	191.7(2)	<.001	16344
Interval duration $\times$ MMSE $\times$ Age	-8128.5	76.8(4)	<.001	16275
<i>Explicit timing task (b)</i>				
Interval duration	-8262.7			16531
Interval duration $\times$ Age	-8220.8	83.7(2)	<.001	16452
Interval duration $\times$ MMSE $\times$ Age	-8128.5	184.7(4)	<.001	16275

Implicit timing task (a)

Interval duration	-2943.8			5896
Interval duration $\times$ MMSE	-2921.7	44.11(2)	<.001	5855
Interval duration $\times$ MMSE $\times$ Age	-2914.6	14.26(4)	.007	5849

Implicit timing task (b)

Interval duration	647.7			5896
Interval duration $\times$ Age	-2937.2	13.24(2)	.001	5886
Interval duration $\times$ MMSE $\times$ Age	-2914.6	45.13(4)	<.001	5849

Table 3. Summary of the model outputs for the explicit timing task.

Fixed Effects	<i>Odds ratios</i>	β	<i>p</i>
(Intercept)	1.082	1.109	0.093
Interval duration	1.842	1.944	<0.001
MMSE	1.034	1.048	0.521
Age	0.987	0.970	0.793
Interval duration $\times$ MMSE	1.245	1.161	<0.001
Interval duration $\times$ Age	0.877	0.906	<0.001
MMSE $\times$ Age	0.923	0.951	0.121
Interval duration $\times$ MMSE $\times$ Age	1.013	1.007	0.430
N _{ID}			85
Observations			14729
Marginal R ² /Conditional R ²			0.30 / 0.38

Figure 3. Interaction effects in the explicit timing task. Panel **A** depicts the interaction between Time and MMSE, whereas panel **B** depicts the interaction between Time and Age. The seven interval durations on the x-axis represent the actual durations used in the task.

Implicit timing task. As for the explicit timing task, model comparison (Table 2) showed that the best fitting model was again the full model including Interval duration, MMSE and Age variables. Visual inspection of the residuals showed that the model was a bit stressed. Thus, trials with absolute standardized residuals higher than 2.5 standard deviations were considered outliers (Baayen & Milin, 2010) and removed (3% of the trials). The full model was, then, refitted on the resulting dataset (a summary of the model output is presented in Table 4). Figure 4 shows an overall increase in RT with lower MMSE scores (MMSE main effect) and with increased Age values (Age main effect). Concerning the foreperiod effect (i.e., shorter RTs with longer interval durations), it decreased with lower MMSE scores (Interval duration $\times$ MMSE interaction), but increased with greater age (Interval duration $\times$ Age interaction). The Interval duration $\times$ MMSE $\times$ Age three-way interaction was not significant.

Table 4. Summary of the model outputs for the implicit timing task.

Fixed Effects	<i>Estimates</i>	β	<i>p</i>
(Intercept)	6.119	-0.002	<.001
Interval duration	-0.064	-0.166	<.001
MMSE	-0.161	-0.328	<.001
Age	0.118	0.279	.001
Interval duration $\times$ MMSE	-0.014	-0.027	<.001
Interval duration $\times$ Age	-0.006	-0.011	.018
MMSE $\times$ Age	0.017	0.029	.632
Interval duration $\times$ MMSE $\times$ Age	0.002	0.003	.507
N _{ID}			85
Observations			14976
Marginal R ² /Conditional R ²			0.18/0.66

Figure 4. Interaction effects in the implicit timing task. Panel A depicts the interaction between Time and MMSE, whereas panel B depicts the interaction between Time and Age. The seven interval durations on the x-axis represent the actual durations used in the task.

Discussion

In this study we compared explicit and implicit timing in both healthy and pathological aged populations, thus, extending recent research on explicit and implicit timing in healthy aging (Droit-Volet et al., 2019).

As concerns explicit timing, we reasoned that if age-related differences in explicit timing reflect the functioning of a slower clock in older participants, this should be indexed by a leftward shift of the psychometric function with increased age. By contrast, if age-related differences in temporal performance depend on the reduced cognitive functioning of older adults, one would expect a flatter psychometric function with lower MMSE scores. These predictions were only partly supported by our results, given that a flatter psychometric function was not only observed for lower MMSE scores but also for greater age. Collectively, our results showed that both healthy cognitive aging and pathological cognitive decline were associated with less precise temporal judgments in the time bisection task.

The lack of evidence for a systematic over- or under-estimation bias in duration judgments, which was indicated by the non-significant main effects of MMSE and age variables, accords well with previous time bisection studies in healthy (Lamotte & Droit-Volet, 2017; McCormack et al., 1999; Wearden et al., 1997) and pathological aging (Caselli, Iaboli, & Nichelli, 2009; Mioni, Meligrana, et al., 2019). Consistent with this prior literature is also our observation of a flatter bisection curve for lower MMSE scores and increased age. A possible interpretation for the flatter psychometric function associated with decreased MMSE scores or increased age is that more compromised or much older participants had a noisier memory representation of standard durations, which led them to respond “short” to long durations and “long” to short durations. Supporting the role of memory in temporal processing, it has been shown that similar anatomical structures underlie memory and timing functions (Lustig, Matell, & Meck, 2005). Moreover, as stated in the Introduction, a strong link between memory and temporal processes is acknowledged within pacemaker-based accounts of time perception (Block & Gruber, 2014; Matthews & Meck, 2016;

Pouthas & Perbal, 2004; Üstün, Kale & Çiçek, 2017). Framing our results within such models, it is expected that a poor memory representation of the standards would lead to a flatter psychometric function. Another possible, not mutually exclusive, explanation for this flattening is that participants with lower MMSE scores or greater age had more troubles paying attention to stimulus durations throughout the time bisection task. Together with memory processes, attentional functions are also important to successfully perform on explicit timing tasks (Mioni et al., 2020; Pouthas & Perbal, 2004). In any case, regardless of whether memory for- or attention to- durations or both were compromised in our sample of older adults, it seems clear that age and cognitive impairment modulated performance on the time bisection task. Remarkably, neither age nor cognitive impairment altered timekeeping mechanisms per se (i.e., systematic under- or over-estimation of interval durations), but instead they influenced more generalized cognitive processes (e.g., memory and/or attention), as indexed by the finding of a flatter psychometric function in more compromised or much older participants. Future studies should administer older adults with tasks requiring judgement of both temporal and non-temporal magnitudes (e.g., weight, brightness) to directly compare age-related deficits in specific temporal and other non-temporal cognitive dimensions.

In contrast to the explicit timing task, in the implicit timing one the task goal itself was non-temporal as participants had to simply respond to the onset of the cross and no explicit judgement of the interval duration (or foreperiod) separating the cross from the thicker circle (see Figure 2, A) was required. The foreperiod effect (i.e., shorter RTs at longer interval durations), as commonly observed in these types of RT tasks, is considered indicative of an implicit processing of time, with participants benefitting from the information afforded by the elapse of time during longer foreperiod trials (Niemi & Näätänen, 1981; Coull & Nobre, 2008). Considering that implicit timing poses less demands on cognitive processes as compared to explicit timing, our original hypothesis was that the best predictor of performance on the implicit timing task should be the participants' age (Droit-Volet et al., 2019). Instead, echoing the results from the explicit timing task, the best fitting model included again interval duration, MMSE scores and age variables. However, unlike the

explicit timing task, MMSE scores and age had different effects on participants' performance. We detail these differences in what follows.

To begin with, the significant main effects of MMSE scores and age showed an overall increase in RT for lower MMSE scores and greater age, in line with the presence of a generalized RT slowing in healthy and pathological aging (Tales et al., 2012). In any case, this pattern does not reflect a deficit in the implicit processing of temporal information, which was instead operationalized by the size of the foreperiod effect, as alluded to above. A close look at Figure 4 clearly depicts that the foreperiod effect increased with greater age, whereas it decreased with lower MMSE scores.

The presence of a larger foreperiod effect in older participants is explained by the fact that they were slower than younger participants at shorter interval durations, but better able to recover at longer durations, thus yielding a steeper foreperiod effect than that displayed by younger participants. Put simply, whereas for younger participants there was less room for improvement from short to longer interval durations, older participants improved their performance at longer interval durations, which is indicative of a preserved ability to implicitly process temporal information. By contrast, although more compromised participants were also slower at shorter interval durations as older participants, they did not manage to fully recover at longer durations. This explains their reduced foreperiod effect as compared to participants with higher MMSE scores. Overall, the dissociation observed in the size of the foreperiod effect between older and impaired participants provides strong evidence in favour of the idea that implicit processing of time can be preserved in healthy, but not pathological, age-related cognitive decline.

The above-described steeper foreperiod effect as function of age is in line with previous studies (Bherer & Belleville, 2004; see also Zanto, Pan, Liu, Bollinger, Nobre, & Gazzaley, 2011), suggesting that older adults have difficulties in preparing to less probable short foreperiod trials. However, as time passes by without target presentation, they can optimize response preparation to targets that will certainly occur at longer foreperiods. Relatedly, it makes sense to hypothesize that

our observation of a smaller foreperiod effect in more compromised participants can be taken as evidence for a greater deficit in monitoring the conditional probability of target occurrence over time (Vallesi et al., 2009).

Taken together, our findings from the implicit timing task open a novel perspective on processing of temporal information in aging by offering the first evidence that implicit processing of time can be spared in healthy age-related cognitive decline. This result holds important clinical and practical implications towards early diagnosis and tracking of the progression of neurodegeneration along the aging continuum. Indeed, the identification of early cognitive markers is of outmost importance to develop effective prevention and help distinguish between normal and pathological age-related cognitive changes. Along this line, our results suggest that a simple RT task measuring implicit time processing could be used as a potential diagnostic tool that poses very little demands on cognitive resources and can be easily administered by both researchers and clinicians. In addition to these practical aspects, our findings documented a clear dissociation between explicit and implicit timing in healthy and pathological aging, both extending previous research in healthy aging (Droit-Volet et al., 2019) and adding to other dissociations reported in children (Droit-Volet & Coull, 2016) and clinical conditions such as Parkinson's disease (Mioni, Capizzi, et al., 2018) and schizophrenia (Ciullo et al., 2018). Overall, coupled with these studies, our findings converge on the idea that implicit timing tasks could offer important insights into processing of time in vulnerable populations because of its fewer demands in terms of attention and memory (i.e., no explicit instructions to pay attention to time neither to memorize durations) as compared to more demanding explicit timing tasks. A path that future research must surely follow is the investigation of the neural mechanisms that are in charge of preserving implicit timing in aged populations. It would be also interesting to find the age point at which performance on explicit and implicit timing tasks starts to diverge to get a comprehensive picture on processing of explicit and implicit timing from a life-span perspective.

A potential caveat to our study is that we exclusively relied on the use of the MMSE and did not employ other neuropsychological tests that could have better defined the cognitive profile of our sample. Although plausible, it should nonetheless be noted that the MMSE is routinely used in clinical practice to screen for cognitive impairment because of its easy procedure and short administration time. As shown here, it proved to be enough sensitive to differentiate performance on explicit and implicit timing tasks, but it would be surely interesting to also apply our research approach to more cognitive screening and neuropsychological tests. Another concern could be that our study did not provide any information on potential differences in temporal processing between AD patients and individuals diagnosed with MCI. As amply discussed above, we were interested in disentangling the effects of age from those related to cognitive impairment regardless of the neurodegenerative condition. However, our findings could be used in the future as an ideal starting point to investigate whether specific neurodegenerative conditions differently affect temporal processing.

In conclusion, the present findings contribute to the understanding of age-related changes in temporal processing by showing different patterns for explicit and implicit timing tasks. Whereas both healthy aging and pathological cognitive decline similarly affected the extra cognitive, non-temporal, processes demanded by explicit temporal judgments, processing of implicit timing instead survived normal age-related changes. This result paves the way to stimulating research avenues and clinical applications in healthy and pathological aging.

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Supplementary Information

Table S1. Descriptive statistics (mean and standard deviation) of our sample.

Male						Female				
		Age	Level of education	MMSE (raw)	MMSE corrected		Age	Level of education	MMSE (raw)	MMSE corrected
	N	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	N	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Without cognitive decline	21	72.19 (6.36)	9.90 (4.46)	29.29 (0.77)	28.01 (1.28)	21	72.86 (6.15)	10.76 (3.87)	29.38 (0.86)	27.82 (1.42)
Mild cognitive impairment	11	73.09 (5.70)	9.54 (4.65)	26.22 (0.93)	24.93 (0.92)	16	71.50 (5.43)	9.00 (4.99)	26.59 (0.90)	25.39 (1.32)
Mild dementia	5	76.20 (10.21)	7.80 (3.27)	22.70 (1.79)	22.14 (1.14)	7	79.14 (6.99)	5.14 (1.46)	21.71 (2.29)	22.13 (3.14)
Moderate dementia	2	86.50 (3.53)	5.00 (0.00)	16.00 (2.83)	16.90 (3.53)	2	74.00 (14.14)	6.50 (2.12)	12.00 (2.83)	12.20 (2.54)

Note: MMSE = Mini Mental Examination State (Folstein et al., 1975). MMSE (raw) indicates participant's performance and MMSE (corrected) indicates the score corrected for age and education (Folstein et al., 1975; for Italian version, Magni et al., 1996). A score between 30 and 28 was the cut-off to define healthy older adults with a normal cognitive functioning; a score between 27 and 25 indicated the presence of Mild Cognitive Impairment (MCI); a score between 24 and 19 denoted a mild dementia, whereas a score between 18 and 10 a moderate dementia.

Table S2. Summary of the model outputs for the explicit timing task from analyses including participants with a proportion of non-given responses lower than .1, .2, .3, or .4, respectively.

	Proportion of non-given responses							
	<.1		<.2		<.3		<.4	
Fixed Effects	<i>Odds ratios</i>	<i>p</i>	<i>Odds ratios</i>	<i>p</i>	<i>Odds ratios</i>	<i>p</i>	<i>Risk Ratios</i>	<i>p</i>
(Intercept)	1.04	0.495	1.06	0.303	1.06	0.25	1.07	0.193
Interval duration	1.98	<0.001	1.99	<0.001	1.88	<0.001	1.86	<0.001
MMSE	1.06	0.398	1.04	0.528	1.04	0.544	1.05	0.424
Age	0.95	0.444	0.98	0.774	0.97	0.62	0.98	0.625
Interval duration × MMSE	1.23	<0.001	1.22	<0.001	1.26	<0.001	1.27	<0.001
Interval duration × Age	0.89	<0.001	0.89	<0.001	0.87	<0.001	0.89	<0.001
MMSE × Age	0.93	0.265	0.92	0.166	0.92	0.176	0.93	0.225
Interval duration × MMSE × Age	1.05	0.015	1.04	0.031	1.04	0.034	1.04	0.013
N _{ID}		65		72		78		82
Observations		11753		12949		13814		14369
Marginal R ² / Conditional R ²		0.330 / 0.423		0.331 / 0.422		0.313 / 0.400		0.305 / 0.393

Table S3. Summary of the model outputs for the implicit timing task from analyses including participants with a proportion of non-given responses lower than .1, .2, .3, or .4, respectively.

	Proportion of non-given responses							
	<.1		<.2		<.3		<.4	
Fixed Effects	<i>Estimates</i>	<i>p</i>	<i>Estimates</i>	<i>p</i>	<i>Estimates</i>	<i>p</i>	<i>Estimates</i>	<i>p</i>
(Intercept)	6.054	<0.001	6.065	<0.001	6.095	<0.001	6.094	<0.001
Interval duration	-0.064	<0.001	-0.066	<0.001	-0.067	<0.001	-0.067	<0.001
MMSE	-0.163	<0.001	-0.103	0.013	-0.119	0.003	-0.117	0.004
Age	0.084	0.017	0.085	0.019	0.107	0.002	0.107	0.002
Interval duration × MMSE	-0.015	<0.001	-0.011	<0.001	-0.012	<0.001	-0.011	<0.001
Interval duration × Age	-0.004	0.186	-0.007	0.006	-0.008	0.002	-0.007	0.004
MMSE × Age	0.005	0.899	0.04	0.299	0.042	0.281	0.044	0.256
Interval duration × MMSE × Age	0.001	0.743	0.004	0.152	0.003	0.252	0.004	0.173
N _{ID}		65		72		78		82
Observations		11619		12936		13932		14605
Marginal R ² / Conditional R ²		0.175 / 0.616		0.123 / 0.630		0.154 / 0.633		0.148 / 0.630