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Meta-analysis of time perception and temporal processing in schizophrenia: Differential effects on precision and accuracy

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ABSTRACT

Numerous studies have reported that time perception and temporal processing are impaired in schizophrenia. In a meta-analytical review, we differentiate between time perception (judgments of time intervals) and basic temporal processing (e.g., judgments of temporal order) as well as between effects on accuracy (deviation of estimates from the veridical value) and precision (variability of judgments). In a meta-regression approach, we also included the specific tasks and the different time interval ranges as covariates. We considered 68 publications of the past 65 years, and meta-analyzed data from 957 patients with schizophrenia and 1060 healthy control participants. Independent of tasks and interval durations, our results demonstrate that time perception and basic temporal processing are less precise (more variable) in patients (Hedges' $g > 1.00$), whereas effects of schizophrenia on accuracy of time perception are rather small and task-dependent. Our review also shows that several aspects, e.g., potential influences of medication, have not yet been investigated in sufficient detail. In conclusion, the results are in accordance with theoretical assumptions and the notion of a more variable internal clock in patients with schizophrenia, but not with a strong effect of schizophrenia on clock speed. The impairment of temporal precision, however, may also be clock-unspecific as part of a general cognitive deficiency in schizophrenia.

1. Introduction

Over the last decades, numerous studies have reported that the perception of time and the processing of temporal information is distorted in clinical disorders such as depression (e.g., Bschor et al., 2004; Kornbrot, Msetfi, & Grimwood, 2013; Thoenes & Oberfeld, 2015; Wyrick & Wyrick, 1977), Parkinson's disease (e.g., Allman & Meck, 2012; Malapani, Deweer, & Gibbon, 2002; Meck, 1996), and schizophrenia (e.g., Martin et al., 2014; Rammsayer, 1990; Roy, Grondin, & Roy, 2012). However, especially in the case of schizophrenia, empirical studies largely differ in the tasks and methods used, and the outcomes of the studies do not always agree. The study of time perception and temporal information processing is of particular relevance in the context of schizophrenia. The notion of mistimed information transfer in schizophrenia by Andreasen et al. (1999) has provided a popular framework for the relationships between basic cognitive impairments and the clinical outcome. However, understanding the precise mechanisms between the cognitive and neurological impairment on the one hand and the patients' symptoms on the other hand still remains unclear. Research on time perception and temporal processing may help to fill this gap.

The present study provides a meta-analytical review of the literature on time perception and temporal processing in schizophrenia from the past 65 years.

With regard to the conceptual and methodological heterogeneity of the literature, it is important to distinguish between different aspects of temporal information processing, and different aspects of human performance in the relevant tasks. These distinctions have not yet been addressed in a systematic review of studies on time perception and temporal processing in schizophrenia.

First, we suggest that *time perception* in the sense of explicit judgments of the durations of events or the production of time intervals should be distinguished from tasks like judging the simultaneity of two events or the order of two stimuli, which we refer to as *temporal processing*. The latter tasks represent lower level processing of temporal stimulus features, and index for example the temporal acuity of the visual or auditory system, but without the necessity of explicit judgments of duration.

Second, the participants' performance can be analyzed in terms of *accuracy*, which indexes the (signed) deviation of a judgment from the

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veridical value, and in terms of *precision*, which refers to the *variability* of the judgments (cf. Grondin, 2010). According to the scalar expectancy theory (SET; sometimes referred to as scalar timing theory), which represents the most influential theory of time perception, humans are able to estimate time on average accurately and precisely (Gibbon, 1977; Gibbon, Church, & Meck, 1984). However, several factors, such as the level of bodily arousal, can lead to systematic deviations of the time estimates from the veridical value, and to less precise temporal judgments (Droit-Volet & Meck, 2007). In the context of clinical disorders, both measures of temporal performance, accuracy and precision, are considered to be altered in schizophrenia (Allman & Meck, 2012; Bolbecker et al., 2014).

Third, apart from these two major distinctions, different tasks involve different components of human information processing and behavior. For example, some tasks that were used to study time perception in schizophrenia require timed motor responses, while other tasks require a perceptual judgment but no temporally precise motor response. A recent meta-analysis on time perception in patients with schizophrenia has considered the latter differentiation (Ciullo, Spalletta, Caltagirone, Jorge, & Piras, 2016). However, the authors did not address the importance of the distinction between time perception and temporal processing, nor the distinction between accuracy and precision. Also, several relevant studies were not included in their meta-analysis.

Before describing our meta-analytic strategy, we now discuss the different tasks used in the relevant literature, and the distinction between accuracy and precision.

1.1. Tasks used to study time perception and basic temporal processing

Concerning the first distinction, tasks used to study *time perception* in general and in the context of schizophrenia encompass the well-established cases of *a) verbal time estimation*, *b) time production*, *c) time reproduction*, and *d) duration discrimination* (cf. Grondin, 2010), as well as *e) rhythm production tasks* (e.g., Vorberg & Wing, 1996).

In *verbal time estimation*, a time interval is presented, defined for instance by the inter-onset interval (IOI) between two brief tones or light flashes or by the onset and offset of a continuous auditory or visual signal, and the participant gives an estimate of this time interval in conventional chronometric units like seconds or minutes (Broadhurst, 1969; Carlson & Feinberg, 1968; Clausen, 1950; Densen, 1977; Dilling & Rabin, 1967; Johnson & Petzel, 1971; Orme, 1966; Pearl & Berg, 1963; Roy et al., 2012; Rutschmann, 1973; Tracy et al., 1998). Such a task is most frequently used for *prospective time estimation*, where the participant is aware that time intervals are to be judged. It can also be used in a *retrospective* manner, however. For instance, the participant could be asked to estimate the duration that has elapsed since the beginning of the experiment, without having been informed at the beginning of the experimental session that such a time estimation will be required (Oyanadel & Buela-Casal, 2014; Rabin, 1957; Tysk, 1983a; Wahl & Sieg, 1980). In this case, usually the perception of longer time intervals (in the range of several minutes to hours) is investigated, compared to intervals in the second or minute range that are typically used in prospective time estimation. It has to be noted that a retrospective verbal estimation task is comprised of a single trial only. As soon as the task includes trial repetitions, it turns into a prospective time estimation task with the participant being informed. Therefore, the retrospective verbal estimation task provides information about the accuracy of temporal performance but not about its precision. The prospective verbal estimation task provides information about both measures of temporal performance, accuracy and precision. The signed deviation of the mean verbal judgment from the veridical duration (*signed error*) measures the accuracy, while the variability of the verbal estimates (e.g., the standard deviation of the estimates across 10 presentations of the same temporal interval; often termed *variable error*) is a measure of precision.

In a *time production task* (*b)*, a time interval is defined in terms of conventional chronometric units, i.e. “2.0 s”, and the participant is required to produce the interval, for example by giving two motor responses marking its beginning and end (Carlson & Feinberg, 1968; Clausen, 1950; Johnson & Petzel, 1971; Nosachev, 1992; Oyanadel & Buela-Casal, 2014; Tysk, 1983b; van der Veen, Roder, & Smits, 2013; Wahl & Sieg, 1980). Sometimes, several repeated productions rather than just a single production are required on a trial (Turgeon, Giersch, Delevoye-Turrell, & Wing, 2012). Note that this special case of time production is different from a rhythm production task (see below *(e)*) because the interval to be produced is defined in chronometric units (e.g., “please press the button once per second”) and not in terms of a presented rhythm. The production task also provides information about both accuracy and precision, similar to the verbal estimation task. An important difference to the verbal estimation task is, however, that the production task requires timed motor actions. For this reason, the behavioral results will not only be affected by changes in the cognitive representation of time intervals or the “clock mechanism”, but also by factors influencing the motor system (for a discussion see Oberfeld, Thönes, Palayoor, & Hecht, 2014).

In a *time reproduction task (c)*, a time interval is presented as in *a)* and the participant reproduces the interval as in *b)* (Carlson & Feinberg, 1968; Clausen, 1950; Roy et al., 2012; Tracy et al., 1998). Thus, the reproduction task combines the perception and the (motor) production of a time interval, and again provides information on accuracy as well as on precision. There are several different variants of the time reproduction task. Besides pressing a key to start and stop the interval, the participants can be instructed to just mark the end of an interval, or to hold down the key continuously during the interval. A recent study by Mioni, Stablum, McClintock, and Grondin (2014) shows that the different reproduction methods are not equivalent to each other. The classic variant involving keypresses to start and stop the reproduction yields the highest accuracy, and the method of continuous key pressing leads to the most precise reproductions.

In the case of *duration discrimination (d)*, often a *two-interval task* is used where two time intervals are presented successively and the participant has to decide which interval was longer and which intervals was shorter (Rammsayer, 1990; Todd, Michie, Budd, Rock, & Jablensky, 2000; Todd, Michie, & Jablensky, 2003; Ulferts, Meyer-Lindenberg, & Gallhofer, 1999; Volz et al., 2001). Based on fitting a psychometric function to the data, or on an adaptive procedure (e.g., Levitt, 1971), the two-interval duration discrimination task provides an estimate of the *duration difference limen*, which is the duration difference between the two stimuli at which the participant is able to identify the longer/shorter interval with, for example, 75% correct responses. The two-interval discrimination task measures precision, and provides an estimate of the point of subjective equality of the duration of the first and second time interval. In *one-interval discrimination tasks*, only a single time interval is presented per trial and has to be compared to a so-called *standard interval*. The standard interval has either been learnt explicitly prior to the discrimination task (Davalos, Rojas, & Tregellas, 2011; Lhamon & Goldstone, 1973; Waters & Jablensky, 2009) or implicitly during the task (Lhamon & Goldstone, 1956). In the latter case, the participant develops an internal representation of an intermediate standard duration based on the processing of different comparison durations that are slightly longer or shorter than the intermediate standard duration (Nachmias, 2006; Oberfeld, 2014). In a third variant, the standard interval is presented on each trial before the to-be-judged time interval, this is termed a *reminder task* (e.g., Lapid, Ulrich, & Rammsayer, 2008). A specific one-interval duration discrimination procedure that has been used frequently in the time perception literature in general and also in patients with schizophrenia is the *temporal bisection task* (Bolbecker et al., 2014; Carroll, Boggs, O'Donnell, Shekhar, & Hetrick, 2008; Carroll, O'Donnell, Shekhar, & Hetrick, 2009b; Davalos, Kisley, & Ross, 2002; Elvevag et al., 2003; Lee et al., 2009; Lee, Dixon, Spence, & Woodruff, 2006; Penney, Meck, Roberts,

Gibbon, & Erlenmeyer-Kimling, 2005). Here, the participant first learns a short and a long *anchor duration* of, for example, 1.0 and 2.0 s, respectively. Subsequently, intermediate durations ranging from 1.0 s to 2.0 s are presented and the participant is asked to categorize these as being either more similar to the short anchor duration or to the long anchor duration. In these one-interval tasks, a psychometric function (cf. Treutwein & Strasburger, 1999) is fitted to the data and provides a measure of sensitivity in the duration discrimination task. For example, half the difference between the 75%- and the 25% points on the psychometric functions is often used as a measure of the duration discrimination limen. The difference limen (DL) is a measure of precision and is correlated to measures of precision obtained for example in the time production task described above (Treisman, 1963), and of course to a DL measured in a two-interval discrimination task. Notably, the one-interval tasks also provide information about the average perceived duration of the stimuli, in terms of the 50%- point on the psychometric function, which in the case of the bisection task is often termed the "bisection point" (BP) (Allan & Gibbon, 1991). The signed deviation of the BP from the veridical value (i.e., the arithmetic or geometric mean of the presented time intervals) can be viewed as a measure of accuracy. The sensitivity (precision) in duration discrimination can also be studied by means of a *temporal deviant detection task*, where not only one or two time intervals are presented, but a rhythmic sequence. In an isochronous rhythmic sequence (constructed as a sequence of identical IOIs), occasional phase shifts (temporal deviants) are presented. These are tones or other events with onsets occurring earlier or later than implied by the isochronous rhythm. The task is to detect such a phase shift (Bourdet, Brochard, Rouillon, & Drake, 2003; Davalos, Kisley, & Freedman, 2005; Turgeon et al., 2012). Based on the participant's detection performance, a difference limen for temporal deviant detection can be determined.

Several variants of *rhythm production tasks (e)* have been used to study potential effects of schizophrenia on time perception. In a *continuation tapping task*, the trial starts with the presentation of an isochronous rhythmic sequence and the participants are asked to tap in synchrony with it (Carroll, O'Donnell, Shekhar, & Hetrick, 2009a; Papageorgiou et al., 2013). After some seconds, the sequence stops and the participants are required to continue their tapping at exactly the same rate. The variability of the produced IOIs provides information about the precision of the internal representation of the to-be-produced IOIs, but also about motor variability. Only few studies also provided information about the mean of the produced IOIs, which could be viewed as a measure of accuracy. The continuation tapping task is closely related to the reproduction task, with the difference that in a reproduction task only one time interval is presented and is reproduced once, while in the continuation tapping task first several identical time intervals are presented in a rhythmic sequence and then the participant is required to reproduce these time intervals several times. In a *synchronization tapping task*, the participants provide motor responses (e.g., by tapping with the index finger on a response key) in synchrony to a continually presented rhythmic sequence (Jirsa, Libiger, Mohr, Radil, & Indra, 1996). The deviation of the taps from the onsets of the stimuli in the rhythmic sequence is analyzed and its variability provides information about precision. This task requires anticipatory motor responses (e.g., Fraisse, 1982): for tapping in synchrony with an isochronous rhythm, the participant needs to time his or her next tap so that the time interval between the preceding rhythmic event and the tap corresponds to the IOIs presented in the rhythmic sequence. For this reason, the synchronization tapping task could be viewed as a rhythmic variant of a reproduction task. However, due to the continuous presentation of the rhythm, the participant receives immediate information about the deviation of his or her tap from the rhythmic event. Thus, the synchronization tapping could be described as a closed-loop task, while the reproduction task is an open-loop task. It has been suggested that synchronization tapping involves automatic and unconscious phase corrections that are different from time judgments obtained in other paradigms (e.g., Repp, 2000). For these reasons, synchronization tapping involves rather different processes than the other time-perception tasks. A third variant of finger tapping is the *spontaneous tapping task* (Delevoye-Turrell, Wilquin, & Giersch, 2012). Here, the participant is asked to tap an isochronous rhythm at a self-selected, subjectively preferred rate. Spontaneous tapping is similar to time production, with several successive productions of the same time interval, except that no interval duration is specified by the experimenter. The variability of the produced time intervals is a measure of precision, while the task provides no information about accuracy because a "veridical value" is not defined here.

Laboratory tasks that have been used to investigate basic *temporal processing* not involving judgments of duration (i.e., not measuring time perception) in patients with schizophrenia are *a) judgments of simultaneity*, *b) temporal-order judgments (TOJ)*, *and c) gap detection*.

In *a)*, two stimuli are presented either successively or simultaneously and the participant has to decide whether the onsets of the two stimuli were synchronous or asynchronous. The participant's performance level is determined based on the IOI between the two stimuli leading to a certain proportion of "simultaneous" responses of, for example, 50%. This is termed the *simultaneity threshold* or the *point of perceived simultaneity*. The smaller the simultaneity threshold, the higher the precision of the participant's judgments, indexing higher temporal resolution of the sensory system (Braus, 2002; Capa, Duval, Blaison, & Giersch, 2014; Foucher, Lacambre, Pham, Giersch, & Elliott, 2007; Lalanne, van Assche, & Giersch, 2012; Martin, Giersch, Huron, & van Wassenhove, 2013; Schmidt, McFarland, Ahmed, McDonald, & Elliott, 2011).

In a *temporal-order judgment (TOJ) task b)*, two different stimuli (e.g., two tones differing in frequency) are presented successively, and the participant has to indicate which stimulus was presented first (Braus, 2002; Capa et al., 2014). The IOI between the two stimuli at which a certain performance level is reached, e.g., 75% correct responses, serves as a measure of temporal resolution (precision). The smaller the IOI that is sufficient to discriminate the temporal order of two stimuli, the higher is the temporal resolution of the sensory system (Hirsh, 1959).

A *gap detection task* (*c)* requires the detection of short gaps of silence in a continuous auditory signal, e.g. white noise (Plomp, 1964). The smallest gap that can be detected reliably (e.g., with 75% correct) serves as the performance measure (e.g., Todd et al., 2000). The performance in tasks *a)* to c*)* provides measures of the temporal acuity (precision) of the information processing system.

1.2. Accuracy versus precision

As discussed above, an important distinction concerns the information provided by the dependent measures. Broadly, the participants' performance in time perception tasks can be analyzed in terms of *accuracy* and in terms of *precision*. The term *accuracy* refers to the deviation of a temporal judgment from the veridical value. As usual, we analyze accuracy in terms of the signed error, which denotes the signed deviation of the mean verbal judgment from the veridical duration. For example, if patients with schizophrenia and healthy controls are required to estimate the duration of a visual stimulus presented for 3.0 s in a verbal estimation task, the average estimate of the patients might be 2.5 s and the average estimate of the controls might be 2.9 s. In this case, the patients show a more negative signed error than the controls, i.e., a stronger underestimation compared to the veridical value than the controls. Thus, the accuracy is affected by systematic shifts in the perceived or produced durations. Note that in some of the studies the accuracy was assessed in terms of the deviation of the estimates from the veridical values divided by the veridical value (relative error), or the ratio between the estimated value and the veridical value. As all of these measures are linear transformations of each other, the effect size estimates are not affected by the choice of the

response measure in the primary studies (cf. Thoenes & Oberfeld, 2015).

A complementary measure of accuracy is the *absolute error*, which is the average deviation of the estimates from the veridical value, regardless of the direction of the deviation. Unfortunately, the absolute error was reported only in one study (Tracy et al., 1998). For this reason, we were not able to include this measure of accuracy in our review.

Apart from the systematic deviations of the estimates from the veridical value (*accuracy: signed error*), the data of many tasks also provide information about the *variability* of the estimates across presentations of the same stimulus. This is termed *precision*, or, in terms of Fechner (1860), the "variable error" (VE). The variable error in a verbal estimation task (for example the standard deviation of the estimates across 10 presentations of the same temporal interval) and the difference limen estimated for example from psychometric functions both measure precision, and are closely related (Treisman, 1963). Note that accuracy and precision provide independent information about performance on a task. For instance, a patient and a healthy control participant might both produce an average verbal estimate of 2.9 s for a visual stimulus with a duration of 3.0 s. However, across 30 trials, the variability of the estimates might be higher for the patient (e.g., standard deviation of 60 ms) than for the control participant (e.g., standard deviation of 40 ms). In this case, both participants show equal accuracy, but the controls shows higher precision.

In tasks measuring temporal processing but not time perception, the dependent measures like the duration of the just-detectable gap in an auditory stimulus can be viewed as a measure of precision while the aspect of accuracy plays no role.

1.3. Task-dependent demands

With regard to the third distinction, different time perception tasks involve different components of human information processing and behavior. While time production, time reproduction, and finger tapping tasks require timed motor responses, verbal time estimation and duration discrimination do not. Also, it is likely that memory processes are involved differently depending on the particular task. Time production and time estimation require the participant to refer to long-term memory representations of time in terms of chronometric units like seconds or minutes. In time reproduction, duration discrimination, and finger tapping, however, the information necessary for doing the task is presented within a given trial, or within the experimental block, so that these tasks are likely to depend on short-term memory or sensory memory rather than on long-term memory.

1.4. Theoretical assumptions concerning time perception and temporal processing in schizophrenia

When reviewing the literature on time perception and temporal processing in schizophrenia qualitatively, the results obtained by means of similar and different tasks are inconclusive so far. However, based on theoretical assumptions, the performance of patients should differ systematically from the performance of healthy control participants. It has been suggested that the clinical symptoms in schizophrenia, such as delusions and hallucinations, may arise from a deficit in the temporal coordination of information processing (Allman & Meck, 2012; Andreasen et al., 1999; Ciullo et al., 2016; Densen, 1977). According to Andreasen et al. (1999), mistimed information transfer in patients with schizophrenia may lead to incorrect connections of thoughts and actions, and to misinterpretations of external and internal processes. Accordingly, the *precision* of basic temporal processing and of judgments of duration (time perception) should be impaired and systematically related to the severity of the typical symptoms in schizophrenia (Bolbecker et al., 2014; Rammsayer, 1990). Moreover, in comparison to control participants, patients with schizophrenia exhibit lower activity in brain areas that are involved in temporal processing and duration judgments (Allman & Meck, 2012). In particular, the cerebellum has been proposed to be affected by schizophrenia, which is involved in precise (motor) timing of short durations in particular (Andreasen & Pierson, 2008). Accordingly, patients with schizophrenia may show impaired precision of time perception and temporal processing, whereas mean duration judgments (accuracy) remain unaffected.

In order to predict in which specific way schizophrenia may influence the performance on the experimental tasks, it seems sensible to consider the influential *pacemaker-accumulator models* of interval timing (Gibbon et al., 1984; Treisman, 1963). Such models assume an *internal clock* consisting of a pacemaker emitting pulses and an accumulator (or counter) collecting these pulses. The perceived length of a time interval is assumed to depend on the number of accumulated pulses. This means that if a participant's clock runs faster, more pulses get accumulated within a specified interval, and therefore the interval is perceived as longer compared to a participant with a slower clock speed. Accordingly, clock speed affects the mean estimates, that is, the *accuracy* of duration judgments in an experimental task. Importantly, depending on the specific task used, different patterns of results are to be expected. In the *verbal estimation* task, an accelerated internal clock causes the accumulation of more pulses during the presentation of the to-be-judged time interval. Hence, if the clock of patients with schizophrenia was accelerated (i.e., "ticking faster"), they should *overestimate* the duration of the time interval compared to control subjects. However, the opposite relation is predicted for a *production* task. According to the internal clock model, a participant starts to accumulate clock pulses at the start signal, and produces the end of the interval as soon as the accumulated number of pulses reaches a value (stored in long term memory) corresponding to for example "2 s". If the internal clock of patients with schizophrenia runs at a faster pace, then they should produce *shorter* intervals than the control subjects, that is, the patients should *underproduce* the time interval compared to healthy controls. As verbal time estimation and time production tasks require the participant to recall long term memory representations of durations, an alternative explanation of effect of schizophrenia on accuracy in these tasks is related to altered memory representations. For example, if a participant's representation of 2 s in long-term memory is incorrect and equivalent to a veridical duration of 1.5 s, the participant would also provide short productions when being asked for productions of 2 s, while showing an overestimation of duration when judging an interval of 2 s.

In a *reproduction* task, a time interval is not specified in terms of time units but it is presented explicitly before the subject is asked to reproduce it. Here, a faster (or slower) accumulation of pulses should affect the representation of the interval to be timed as well as its reproduction. According to the clock models, the accumulation of pulses during the presentation of the time interval, and the accumulation process during the production phase should be affected in the same way. Therefore, clock speed should have no effect on the reproduced duration, so that no differences between patients and controls are to be expected (Carlson & Feinberg, 1968). Beside the speed of the internal clock, the pulse-to-pulse variability (clock variability) might be increased in patients with schizophrenia, which appears plausible based on the theoretical assumptions as discussed above. An increase in clock variability would impair the precision of duration judgments and temporal processing. In a duration discrimination task, for example, an increase in clock variability would be reflected in larger difference limens in patients as compared to controls.

1.5. Structure of the present study

In the present study, we adopted a meta-analytical approach that investigated whether the assumed and reported effects of schizophrenia are substantial by considering the three important distinctions/aspects of, a) time perception versus temporal processing, b) measures of

accuracy versus precision, and c) the specific task used in the study (for example, tasks involving or not involving timed motor responses). Therefore, in a first step, we meta-analyzed the effects of schizophrenia on *accuracy in time perception tasks*. In a second step, we focused on effects on *precision in time perception tasks*. And in a third step, we investigated effects on precision in tasks addressing *basic temporal processing* (measured in temporal simultaneity judgments and temporal-order judgments). Note that these tasks do not provide information about temporal accuracy. Regarding aspect c) discussed above, in each step, we analyzed potential task-specific effects by defining the specific task as a covariate in the meta-analytical model. Thus, if task-specific effects do exist, the analyses allow for attributing such effects to specific task demands, as for example motor or memory demands. We also investigated whether potential effects of schizophrenia are only substantial for specific interval durations. If effects of schizophrenia on time perception and temporal processing do exist irrespective of the temporal tasks, and time intervals used, this would be compatible with a general timing deficit in schizophrenia (Andreasen et al., 1999).

2. Method

2.1. Search strategies and study selection

We searched for relevant studies in Web of Science and Google Scholar. The primary key words were '*schizophrenia*' in conjunction with '*timing*' or '*time*' or '*temporal*'. Additional studies were identified by including the references listed in the studies found in Web of Science and Google Scholar, and by considering the studies that cited the resulting body of literature. Moreover, based on an email list from the "International Conference on Timing and Time Perception", which was held in Corfu in 2014, we sent calls for unpublished data on the topic to > 100 researchers in the field of timing and time perception. This iterative literature search strategy yielded 68 papers (including four conference contributions) that address time perception or temporal processing in schizophrenia, with 59 papers reporting empirical data.

For the meta-analyses, we selected studies according to the following four criteria.

Criterion 1). The studies had to provide data from a group of patients with schizophrenia (or from individuals at high risk of schizophrenia in the case of Penney et al. (2005)) as well as from a control group consisting of healthy adults only. Because healthy participants also tend to produce systematic errors in time perception and temporal processing tasks (e.g., Wearden & Lejeune, 2008), it is uninformative to simply compare judgments of patients, for example verbal time estimates, to the veridical values of the presented time intervals. Hence, for studies that focused on patients with schizophrenia only (e.g., Clausen, 1950; Yang et al., 2004), it is not possible to decide whether the reported deviations of the time estimates from the veridical values are specifically related to schizophrenia. Therefore, systematic comparisons between patients and healthy control participants on the single study level are required.

Criterion 2). The report of sample sizes, means, and standard deviations of the response measures, or t or F-values had to be sufficiently detailed in order to compute effect size estimates (Hedges' g) and their variance. If this was not the case, we contacted the authors of the study for papers published after the year 2000 and asked for additional information.

Criterion 3). At least one of the common time perception or temporal processing tasks as listed above had to be used.

Criterion 4). The reported response measures and analyses had to describe the participants' performance in terms of accuracy, precision, or both (separately). Unfortunately, this was not the case for all studies, because many papers did not use the established psychophysical tasks or data analyses. For example, as described above, one-interval discrimination tasks provide information about both precision (in terms of the difference limen) and about accuracy (in terms of the 50% point on the psychometric function) if psychometric functions are fitted to the data. However, several studies analyzed only the proportion of correct responses (e.g., Davalos, Kisley, Polk, & Ross, 2003; Davalos et al., 2002), which is affected by both accuracy and precision. For example, a low proportion correct in the one-interval discrimination task could be due to an imprecise perception of the temporal intervals (precision), but also to a systematic over- or underestimation (accuracy). As a second example, patients with schizophrenia might be less precise in their perception of the time interval than control subjects, but at the same time show a smaller tendency towards over- or underestimation (i.e., smaller signed error). In this case, the effects of schizophrenia on precision and accuracy could cancel, resulting in no difference in proportion correct between the two groups.

Only 29 of the 59 empirical studies met these four criteria and were considered for further analyses (see Appendix Table A.1). Lhamon and Goldstone (1973) reported two experiments investigating two independent samples of participants. Therefore, in the analyses, their first and second experiment were treated as two separate studies, resulting in a total of 30 independent studies entering the analyses.

2.2. Description of the studies

The 30 studies included in this meta-analysis provided data from a total of 2017 participants (957 patients with schizophrenia and 1060 healthy control participants). Overall, there were 714 male and 243 female participants in the patient samples, and 624 male and 436 female participants in the control samples. The mean age of patients with schizophrenia was 35.56 years (SD = 6.22 years), and 33.38 years (SD = 6.23 years) for healthy control participants (mean age weighted with regard to the sample size). Three studies did not provide sufficient information about their participants' age (Bolbecker et al., 2014; Lhamon & Goldstone, 1973; Wahl & Sieg, 1980). The median publication year of the studies included in the analyses was 2004 (range: 1956 to 2014).

In 22 studies (73.3%), patients were diagnosed according to DSM-II, DMS-III, DSM-IV, ICD-9, or ICD-10 criteria (see Appendix Table A.2). A minority of 8 studies (26.7%) did not specify the diagnostic criteria used. These studies usually recruited hospitalized patients that were currently treated in psychiatric clinics. In one of the studies not reporting the diagnostic criteria (Braus, 2002), scores of the patient group on the Brief Psychiatric Rating Scale (Overall & Gorham, 1962) were reported. The "clinical" sample in the study by Penney et al. (2005) was comprised of participants at high genetic risk for schizophrenia (offspring of patients diagnosed with schizophrenia).

In most studies, some patients were under medication, others not. The exact number of medicated participants was often not reported, and only one study reported separate data for participants on and off medication (Braus, 2002). Three studies reported that their participants did not receive medication for at least one week prior to testing (Broadhurst, 1969; Johnson & Petzel, 1971; Penney et al., 2005). In most studies, patients were (partially) treated with neuroleptics (chlorpromazine equivalents).

Appendix Table A.2 provides an overview of study-specific diagnostics and data on age and gender as far as reported by the studies. Also, covered tasks, interval durations, and dependent measures for each study are described. The transcription of the data from the studies was double-checked by independent observers.

2.3. Preprocessing and effect size estimates

Two studies (Braus, 2002; Schmidt et al., 2011) reported data for two samples of patients with schizophrenia (medicated vs. unmedicated and first episode vs. chronic schizophrenia). For both studies, we averaged the reported data (means and standard deviations; weighted with regard to the sample size) across the two patient samples.

Based on the reported means, standard deviations, and sample sizes

for patient groups (M_s, SD_s, n_s) and control groups (M_c, SD_c, n_c), we calculated Hedges' g as an effect size index, which is an estimate of the standardized mean difference between the two populations. According to Hedges and Olkin (1985), g is defined as shown in Equation Eq. B.1, where s is the pooled sample standard deviation (see Eq. B.2). According to Hofmann, Sawyer, Witt, and Oh (2010), the magnitude of g may be interpreted based on the conventions for the common effect size estimator d (small: ≥ 0.2; medium: ≥ 0.5; large: ≥ 0.8) (Cohen, 1988).

For eight studies (Capa et al., 2014; Carroll et al., 2009a; Elvevag et al., 2003; Giersch et al., 2009; Johnson & Petzel, 1971; Lalanne et al., 2012; Lhamon & Goldstone, 1973; Turgeon et al., 2012), because means and standard deviations were not reported in sufficient detail, g was calculated based on the presented F values and sample sizes (see Eq. B.3, Rosnow & Rosenthal, 1996). For Schmidt et al. (2011), g was calculated based on the reported t value and the sample sizes (see Eq. B.4, Rosnow & Rosenthal, 1996). When g was computed from F or t values, the sign of g was determined based on the reported means for the patient group and the control group.

Based on g and the reported sample sizes, we then determined the asymptotic variance of g. According to Hedges and Olkin (1985), the asymptotic variance of g, denoted $Var(g)$, is calculated as shown in Eq. B.5.

Following the preprocessing explained above, one value of g (and $Var(g)$) was computed for each pair of means reported in the selected studies. Because finger tapping tasks were rare in the resulting body of studies that entered the analyses, we considered continuation tapping (Carroll et al., 2009a) as time reproduction, as explained above. None of the analyzed studies used synchronization or spontaneous tapping.

As pointed out above, it is particularly important to consider that according to the internal-clock model (Treisman, 1963), an under-production of duration in time production task goes along with an overestimation of duration in verbal estimation tasks. For this reason, for measures of accuracy (signed error, bisection point), positive values of g reported in our analyses always indicate an overestimation of duration in patients relative to control participants in time estimation and bisection tasks, under-production in patients relative to control participants in time production tasks, and under-reproduction in patients relative to control participants in time reproduction tasks. This important aspect was addressed in many studies (e.g., Wahl & Sieg, 1980), but not in the meta-analysis by Ciullo et al. (2016). For measures of precision (difference limen, Weber ratio, coefficient of variation, d', etc.), negative values of g reported in our analyses always indicate lower precision in patients relative to control participants.

Most studies reported several pairs of means for the same sample and task. Usually, this was due to testing multiple interval durations or different modalities. In our analysis, we averaged across these multiple values for g, and then computed $Var(g)$ according to Eq. B.5, resulting in one value of g and $Var(g)$ for each combination of sample and task (see Appendix Table A.3). The effect size estimates from the different studies were aggregated according to the discussed differentiations between time perception vs. temporal processing and measures of accuracy vs. precision. Potential effects of schizophrenia on 1) accuracy in time perception tasks, 2) precision in time perception tasks, and 3) precision in temporal processing tasks were analyzed separately by means of random effects meta-regression models (van Houwelingen, Arends, & Stijnen, 2002). In each analysis, the task (as used by each study) was entered as an effect-coded covariate in order to investigate potential task-dependent effects, which might be related to different memory- or motor-related demands (see above). Using the SAS PROC MIXED procedure (Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006) for each analysis, the meta-regression model provided an estimate of the pooled effect size and its confidence interval (fixed effect). The degrees of freedom were calculated according to Kenward and Roger (1997). The model also provided a Type 3 test for the influence of task (the covariate) on the effect of schizophrenia (fixed effect), and least-squares means as estimators of effect size for each task (level of the covariate). These estimates represent predicted population marginal means, based on the estimated fixed-effects parameters (Littell et al., 2006). Finally, the analysis provides an estimate of the between-study variance (van Houwelingen et al., 2002).

In an additional step of analysis, we investigated whether differences between patients with schizophrenia and control participants in time perception may depend on the interval durations that have been used in the studies. Based on the preprocessed data, we grouped the interval durations to four different interval ranges: *ultra-short* (< 1 s), *short* (1–10 s), *medium* (10 s–10 min), and *long* (> 10 min) (for study-specific interval durations see also Appendix Table A.2). Here, we averaged across different tasks used, which provided one value of g and - according to Eq. B.5 - one $Var(g)$ for each combination of sample and interval range (see Appendix Table A.4). We fitted two meta-regression models, one for accuracy in time perception, and one for precision in time perception. In both models, interval range was entered as an effect-coded covariate. Note that interval duration is not defined in tasks measuring temporal processing.

Each analysis was repeated once under consideration of potentially outlying data points. We used regression diagnostics to identify outlying data. Following the recommendations by Viechtbauer and Cheung (2010), we analyzed the externally studentized residuals (also called the studentized deleted residuals) and the DFFITS index proposed by Belsley, Kuh, and Welsch (1980) as a measure of the influence of a single observation. Following Belsley et al. (1980), externally studentized residuals with an absolute value exceeding 1.96, or with an absolute DFFITS value exceeding $2\sqrt{p/n}$, where n is the number of effect sizes analyzed in the model, and p is the number of levels of the covariate (task), were defined as outliers.

3. Results

3.1. Accuracy of time perception

The single-study effect sizes, task-specific pooled effect sizes, and the overall pooled effect size for accuracy in time perception are displayed in Fig. 1. As shown in Table 1, the accuracy of time perception (signed error) of patients did not differ significantly from healthy controls. The difference between patients and healthy controls remained non-significant after exclusion of three outliers (see Table 1).

The Type 3 test indicated a marginally significant influence of the covariate task on the effect of schizophrenia, $F(3, 19) = 2.53$, $p = 0.088$. Based on the outlier-corrected data, this effect reached statistical significance, $F(2, 16.4) = 5.72$, $p = 0.013$. Least-squares means (as presented in Fig. 1 and Table 2; reported for outlier-corrected data) indicated overestimation of duration (underproduction) in time production tasks in patients with schizophrenia as compared to control participants. In verbal time estimation, there was also a tendency towards overestimation in patients as compared to control participants, but this effect was only marginally significant. In temporal bisection tasks, the data show the opposite effect. Here, relative to healthy controls, patients classified the duration of a presented comparison interval as *short* more often than as *long* (i.e., the bisection point was higher), which could be viewed as an *underestimation* of duration. The estimated effect size for time reproduction was statistically insignificant and close to zero. Note that during outlier correction the two studies applying time reproduction were excluded from the analysis.

In the analysis including time interval range as covariate, the effect of schizophrenia on the accuracy of time perception did not significantly depend on interval range, $F(3, 19) = 1.46$, $p = 0.256$ (outlier corrected: $F(3, 18) = 2.61$, $p = 0.083$). The outlier-corrected least-squares means (Table 3) showed a significant effect of schizophrenia at medium intervals (patients overestimated time intervals), but not at other interval ranges.

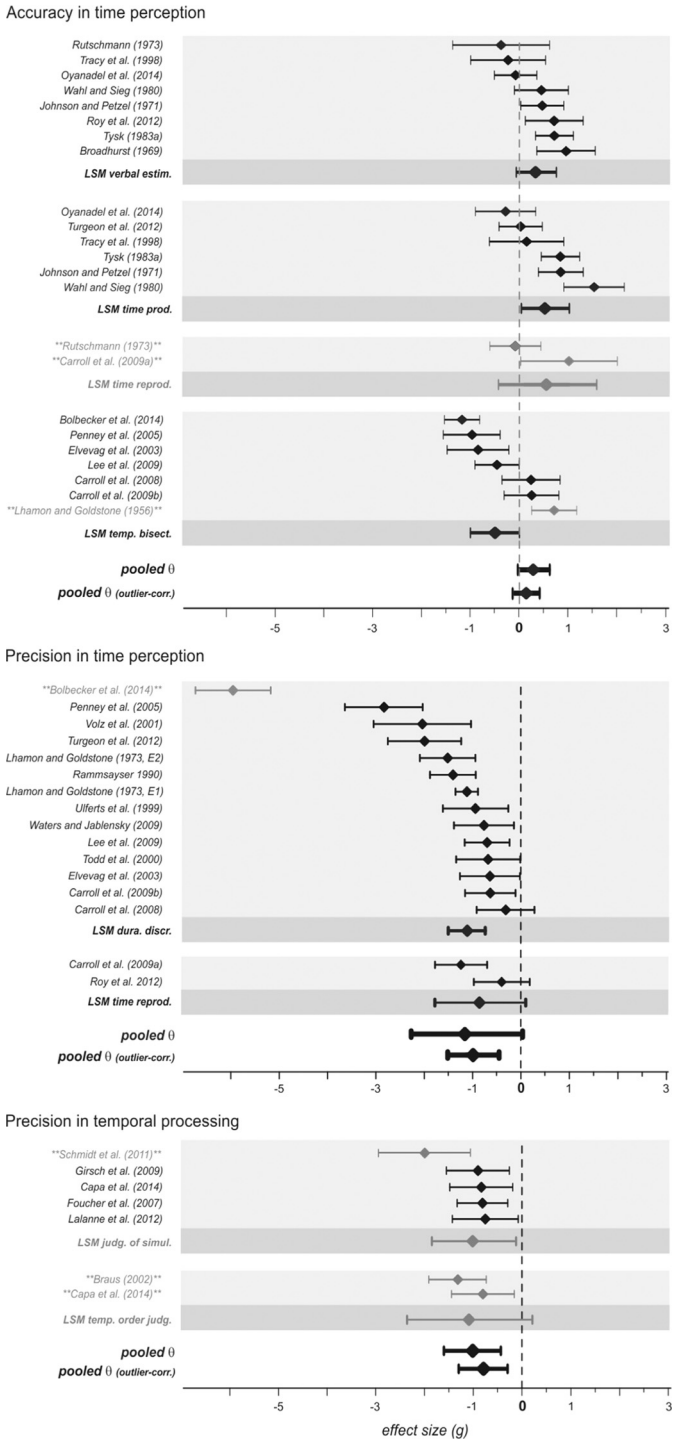

Fig. 1. Forest plot showing effect size estimates (Hedges' *g*) and corresponding 95% confidence intervals grouped by the three analyzed measures (accuracy in time perception, precision in time perception, and precision in temporal processing). Rows denoted by author and year denote original studies, "LSM" denotes least-squares means (marginal means), and "pooled θ" represents pooled θ estimates according to the random-effects meta-regression analyses. Studies identified as outliers are indicated by grey ink and **.Note. For accuracy, positive values of *g* indicate an overestimation of duration in patients relative to control participants in verbal estimation (*verbal estim.*) and bisection tasks (*temp. bisect.*), under-production in patients relative to control participants in time production tasks (*time prod.*), and under-reproduction in patients relative to control participants in time reproduction tasks (*time reprod.*). For precision, negative values of *g* indicate lower precision in patients relative to control participants. *Dura. discr.*: duration discrimination (one- and two-interval tasks). *Judg. of simul.*: judgment of simultaneity. *Temp. order judg.*: temporal-order judgments. The LSMs for accuracy in time reprod. and precision in judg. of simul. and temp. order are based on the analyses including outlying data (for these three, the corresponding outlier-corrected analyses did not yield reliable LSMs).

3.2. Precision of time perception

As seen in Fig. 1, the precision of duration judgments was significantly lower in patients with schizophrenia than in healthy controls. As shown in Table 1, this effect remained significant after excluding one outlier (Bolbecker et al., 2014), and was large according to the classification of Cohen (1988).

The influence of task (duration discrimination vs. time reproduction) on the effect of schizophrenia on precision in time perception was not significant, $F(1, 13.2) = 0.45$, $p = 0.512$ ($F(1, 10.2) = 0.44$, $p = 0.520$, for outlier-corrected data). There was also no significant effect of task when differentiating between the different types of duration discrimination tasks (two interval, temporal bisection, one interval reminder, temporal deviant detection) in an additional analysis, $F(5, 9.73) = 0.18$, $p = 0.964$ ($F(5, 7.4) = 0.55$, $p = 0.737$, for outlier-corrected data). As shown in Table 2, least-squares means indicated large effects for each discrimination task, ranging from $\theta = -1.00$ to -1.99. Note that for temporal deviant detection, the effect size estimate was based on a single study only.

Regarding the second covariate, the effect of schizophrenia on the precision of time perception did not depend on interval range, $F(1, 17) = 0.02$, $p = 0.887$ (outlier corrected: $F(1, 13.5) = 1.37$, $p = 0.263$). As indicated by the LSMs (Table 3), a significantly negative pooled effect size was obtained at both ranges that had been tested by the studies, short as well as ultra-short, indicating more variable duration judgments in schizophrenia patients relative to healthy controls, as in the main analysis.

3.3. Precision of temporal processing

As seen in Table 1, the effect of schizophrenia on precision was also significant for temporal processing tasks, and it was similar in size to the effect of schizophrenia on precision in time perception tasks. Even though the estimated effect size was influenced by outlying data (three data points were identified as outliers), the effect remained large and statistically significant after correction. Note that the outlier-corrected results as presented in Table 1 are based on a fixed effects model, because based on the four remaining effect sizes within one task (simultaneity judgment), the random effects model did not converge.

After the exclusion of outliers, all remaining studies applied simultaneity judgment tasks. Including outlying data, there was no significant effect of the covariate task, $F(1, 2.12) = 0.20$, $p = 0.694$, i.e., the effect size estimates did not differ between simultaneity judgment and temporal-order judgment.

4. Discussion

Based on a total of 957 patients with schizophrenia and 1060 healthy control participants (30 original studies), we investigated the effects of schizophrenia on the accuracy and precision of time perception and temporal processing.

4.1. Effects on accuracy of time perception

Overall, the meta-analysis showed no significant effect on the accuracy of time perception. On average, the signed error of duration judgments did not differ significantly between patients and controls. However, the effect of schizophrenia on the accuracy of time perception depended on the task, at least for outlier-corrected data. Patients with schizophrenia tended to overestimate duration in verbal time estimation relative to controls, and showed a significant underproduction of duration in time production tasks. As explained above, this pattern of effects indicates an accelerated internal clock in patients (Treisman, 1963) or an altered representation of duration in long term memory. A different pattern was observed in temporal bisection tasks. Here, relative to healthy controls, patients with schizophrenia underesti-

Table 1
Pooled effect size estimates (θ). The table shows the results from the meta-regression models with task as covariate, for the influence of schizophrenia on accuracy and precision in time perception (TP) and temporal processing tasks (TPR).

	N ind. samples	*N* effect sizes	θ	CI_L	CI_U	*t*	*df*	*p*	τ^2	SE_{τ^2}	p_{τ^2}
Accuracy TP	17	23	0.29	−0.04	0.63	1.83	19	0.084	0.32	0.13	0.014
outlier-corr.	14	20	0.14	−0.14	0.41	1.05	16.4	0.308	0.25	0.12	0.027
Precision TP	16	16	**−1.17***	−2.29	−0.05	2.25	13.2	0.042	1.80	0.73	0.014
outlier-corr.	15	15	**−0.99***	−1.53	−0.44	4.01	10.2	0.002	0.34	0.19	0.070
Precision TPR	6	7	**–1.03***	−1.63	−0.43	7.01	2.1	0.017	0.02	0.11	0.868
outlier-corr.	4	4	**−0.83***	−1.33	−0.33	5.28	3	0.013	n.d.	n.d.	n.d.

Note. "*N* ind. samples": number of studies/independent samples (i.e., the sample size on level 1). "*N* effect sizes": number of single effect sizes that were entered into the corresponding model (i.e., the sample size on level 2). θ: pooled effect size estimate. CI_L and CI_U are the lower and upper bounds of the 95% confidence interval, respectively, and *t*, *df*, and *p* refer to a test of θ against 0. τ^2: estimate of the inter-study variance. SE_{τ^2}: standard error of τ^2. p_{τ^2} refers to a test of SE_{τ^2} against 0. n.d.: inter-study variance is not defined in the fixed effects model. Bold font and * indicates statistically significant results ($p < 0.05$).

mated duration, in the sense that they judged the comparison durations as short more often than controls did (corresponding to a higher bisection point in patients). This is not in accordance with the results obtained for verbal estimation and production tasks. It has been reported earlier that temporal bisection and verbal time estimation/time production tasks may provide diverging results (e.g., Wearden, 2008). In fact, in a bisection task, an alteration of clock speed should affect the memory representations of the anchor durations during the learning phase and the perception of the intervals during the classification phase in a similar way, so that no systematic shift of the bisection point is to be expected. For this reason, the shift of the bisection point could represent a different type of response bias that is not directly linked to differences in clock speed. As the results from verbal time estimation tasks und time production tasks are quite consistent, we conclude that effects on the accuracy of time perception do not depend on motor demands. In time reproduction tasks, patients did not differ significantly from controls. This result was expected, because according to the internal clock model changes in clock speed should not affect the accuracy in time reproduction, as explained above. Because only two studies applied time reproduction tasks, this result has to be viewed cautiously. Moreover, the two studies were classified as outliers in the meta-regression with task as covariate. Note also that the classic time reproduction used in one of the studies and the continuation tapping tasks used in the other study could differ because in continuation tapping there is a possibility of a drift in the representation of the standard (target) interval during the tapping phase. In a task with single reproductions, where the target interval is presented before each trial, such a drift could not occur.

Across tasks, the estimated effect of schizophrenia on accuracy in time perception did not differ significantly between the four duration ranges (ultra-short < 1 s, short 1–10 s, medium 10 s – 10 min, large > 10 min), although descriptively, the overestimation in patients was most pronounced at medium intervals.

Table 3
Estimated effect sizes (θ_{LSM}) for each interval range for measures of accuracy and precision in time perception, as provided by least–squares means computed in the outlier-corrected meta-regression models with interval range as covariate.

Interval range	*N* studies	θ_{LSM}	CI_L	CI_U	*t*	*df*	*p*
Accuracy							
Ultra-short	7	−0.37	−0.85	0.11	−1.61	18.0	0.125
Short	6	0.10	−0.41	0.61	0.41	18.0	0.687
Medium	6	**0.54***	0.04	1.05	2.25	18.0	0.037
Long	3	0.27	−0.44	0.98	0.79	17.9	0.439
Precision							
Ultra-short	10	**−0.85***	−1.25	−0.45	−4.56	13.6	< 0.001
Short	9	**−1.17***	−1.59	−0.74	−5.87	13.5	< 0.001

Note. Ultra-short < 1 s; short 1–10 s; medium 10 s–10 min, large > 10 min; The concept of duration does not apply to temporal processing tasks; Bold font and * indicates statistically significant results ($p < 0.05$).

4.2. Effects on precision of time perception and temporal processing

In contrast to the ambiguous and rather small effects of schizophrenia on accuracy, the precision of time perception is clearly impaired in patients with schizophrenia. Relative to control participants, patients' judgments were significantly more variable. This effect is large across all

Table 2
Estimated effect sizes (θ_{LSM}) for each task, for measures of accuracy and precision in time perception, as provided by least-squares means computed in the outlier-corrected meta-regression models with task as covariate.

Task	Subtasks	*N* studies	θ_{LSM}	CI_L	CI_U	*t*	*df*	*p*
Accuracy TP								
Verbal estimation		8	0.38	−0.06	0.82	1.82	17.0	0.087
Time production		6	**0.53***	0.03	1.03	2.25	16.3	0.039
Duration discrimi. (Temp. bisection)		6	**−0.50***	−0.99	0.00	2.12	15.9	0.0498
Precision TP								
Time reproduction		2	−0.82	−1.84	0.19	1.80	10.1	0.102
	Reprod.	*1*	*−0.39*	*−2.05*	*1.27*	*0.56*	*7.0*	*0.592*
	Contin. tapping	*1*	*−1.24*	*−2.89*	*0.42*	*1.78*	*6.7*	*0.120*
Duration discrimi.		13	**−1.15***	−1.56	−0.74	6.26	10.7	< 0.001
	Two interval	4	**−1.22***	−2.07	−0.38	3.33	8.1	0.010
	Temp. bisection	6	**−1.00***	−1.68	−0.31	3.49	6.7	0.011
	One interval reminder	2	−1.15	−2.32	0.03	2.29	7.2	0.055
	Temp. deviant detection	*1*	***−1.99****	*−3.68*	*−0.30*	*2.67*	*9.0*	*0.026*

Note. Categories including data from one single study only are indicated by *italics*. Temporal bisection, one-interval reminder, and temporal deviant detection represent one-interval duration discrimination tasks. In the analysis of precision in temporal processing, both studies applying temporal-order judgment were classified as outliers. Accordingly, no LSMs are provided for temporal-order judgment and the LSM for judgment of simultaneity corresponds to the pooled effect size (θ) in the outlier corrected analysis of precision in temporal processing (Table 1). Bold font and * indicates statistically significant results ($p < 0.05$).

tasks and duration ranges that have been tested by the original studies. As the effect of schizophrenia on precision did not differ significantly between discrimination tasks and reproduction tasks, it cannot be attributed to task-specific (e.g., motor) demands. Moreover, the effect size estimates for precision of temporal processing are comparable to those determined for precision of time perception. Hence, irrespective of the specific temporal task and interval duration used, the results from our meta-analysis indicate a general timing deficit in schizophrenia regarding the variability of temporal judgments. In terms of the pacemaker-accumulator model (Gibbon et al., 1984), the internal clock of patients is ticking with larger variability. These results support the notion of generally mistimed information processing in patients with schizophrenia that may lead to incorrect connections of thoughts and actions (Andreasen et al., 1999). However, higher variability in patients in both duration judgments and basic temporal processing, or at both sub- and suprasecond durations (cf. Fraisse, 1963; Lewis & Miall, 2003a), could either be due to a common mechanism, like increased variability of an internal clock, or to different neuropsychological mechanisms. Patients with schizophrenia exhibit lower activity in brain areas such as the striatum, the supplementary motor area, and the insula, which were reported to be involved in duration judgments (Allman & Meck, 2012; Coull, Cheng, & Meck, 2011; Davalos et al., 2011). These structures as well as the cerebellum (Ivry & Spencer, 2004) were reported to be more strongly activated in a duration discrimination task than in a temporal order judgment task (Smith, Taylor, Lidzba, & Rubia, 2003), and cerebellar activation was higher at subsecond durations (Lewis & Miall, 2003a), where time perception is often supposed to be automatic (Lewis & Miall, 2003b). Note that the activity of the cerebellum is also reduced in patients with schizophrenia (Andreasen & Pierson, 2008; Foucher et al., 2007). Thus, it is possible that different neural mechanisms are involved in duration judgments for sub- and suprasecond intervals, or in tasks like temporal order judgments representing basic temporal processing without duration judgments.

In this regard, it should be noted that a decreased precision in patients with schizophrenia may not be limited to temporal judgments but may be caused by a general deficiency in cognitive processes (Davalos et al., 2002). For example, control of selective attention, which represents a key capability to perform well on temporal tasks, is generally affected in patients with schizophrenia (Lapid, Ulrich, & Rammsayer, 2009). In order to systematically dissociate temporal-performance deficits from general cognitive impairments, future studies on time perception and temporal processing in patients with schizophrenia and other clinical populations need to administer tests on variables of general cognitive performance. If the impairment in precision is indeed specifically related to temporal tasks, the results from such studies would provide even stronger evidence for the notion of mistimed information transfer in schizophrenia patients (Andreasen et al., 1999). In the past, parallel measures of general cognitive performance have been obtained by a few studies only, indicating that deficits are rather specific to temporal abilities. For instance, Capa et al. (2014) found no correlation between timing performance and measures of sustained attention, and Elvevag et al. (2003) reported that duration discrimination performance did not correlate with working memory abilities in a sample of patients with schizophrenia. Moreover, an explanation for the temporal deficits in terms of a general cognitive deficiency in schizophrenia may be challenged by the diverging results for measures of precision and accuracy. However, in order to draw firm conclusions on this matter, more studies on time perception and temporal processing in patients with schizophrenia need to consider possibly confounding factors, such as memory and attention.

A very robust finding is that the mismatch negativity (MMN) in EEG responses (e.g., Näätänen, Paavilainen, Rinne, & Alho, 2007) is reduced in schizophrenia (e.g., Umbricht & Krljes, 2005). The MMN is a negative component of the auditory event-related potential. It is elicited by changes in the auditory stimulus, and was proposed to reflect the accuracy of the representation of the dimension on which the changes occur (e.g., duration, pitch) at central processing stages in the brain (e.g., Näätänen & Alho, 1997). The reduction in MMN amplitude has been attributed to changes in the NMDA-type neurotransmitter system (Gil-Da-Costa, Stoner, Fung, & Albright, 2013; Javitt, Steinschneider, Schroeder, & Arezzo, 1996). However, a reduced MMN in schizophrenia is found not only for responses to duration differences, but to a large variety of stimulus differences, although for duration deviants the effects of schizophrenia are particularly strong (Umbricht & Krljes, 2005). Thus, at present it seems unclear whether schizophrenia-related characteristics of the NMDA system play a major role for the reduced precision in time perception and temporal processing.

4.3. Potential effects of medication

It has to be considered that most of the studies included patients who were on medication or in psychotherapy. This might have led to an underestimation of effect sizes. The failure of many studies to provide detailed information concerning the number of subjects under medication, did not allow controlling for possible effects of medication and psychotherapy. As treatment is applied in order to reduce symptoms, possible effects of schizophrenia on time perception and temporal processing might also decline in subjects that are under medication or in psychotherapy. Hence, the inclusion of patients that received some sort of therapy reducing symptom severity probably led to an underestimation of the pooled effect sizes reported in this meta-analysis. In this regard, we checked which of the studies correlated measures of accuracy and precision with measures of symptom severity. However, only six studies carried out such analyses (Bolbecker et al., 2014; Capa et al., 2014; Foucher et al., 2007; Giersch et al., 2009; Roy et al., 2012; Turgeon et al., 2012). None of these reported significant correlations between measures of symptom severity and measures of time perception and/or temporal processing. Similar results have also been reported by a recent review on temporal information processing in schizophrenia (Giersch et al., 2015). Unfortunately, it was not possible to include medication status as a covariate, because only one study (Braus, 2002) analyzed the effects of schizophrenia on time perception separately for patients on and off medication. The results from this particular study did not indicate differences in performance between patients on and off medication. Penney et al. (2005) investigated time perception abilities in a sample of individuals at high risk of schizophrenia. As none of the participants was actually suffering from schizophrenia, all participants were off medication. Indeed, compared to the other studies that usually tested (partially) medicated patients, the results by Penney et al. (2005) indicated larger effects of schizophrenia on the accuracy and precision in temporal bisection tasks. Participants at genetically high risk of schizophrenia significantly underestimated the duration of the comparison intervals and showed strongly increased variability in their duration judgments. These results support the notion that due to medication artifacts, the effects of schizophrenia might be even larger than determined in our analyses.

Moreover, it has to be noted that medicated patients with schizophrenia often receive dopamine antagonists, such as haloperidol (Allman & Meck, 2012). Thus, dopaminergic activity in patients most likely exhibits substantial intra- and inter-individual differences. Evidence from animal as well as human research suggests that decreased dopaminergic activity is related to a deceleration of clock speed (underestimation of time intervals) while increased dopamine levels usually cause opposite effects (e.g., Cheng, Ali, & Meck, 2007; Jones & Jahanshahi, 2009; Meck, 1996; Rammsayer, 1993; Wiener, Lee, Lohoff, & Coslett, 2014). Accordingly, the mixed effects reported for schizophrenia on the accuracy of time perception might be mediated and explained by fluctuating dopamine levels and therefore strongly vary within and between patients. Even though this is methodologically challenging, it would be interesting to consider direct measures of dopamine levels or to use psychopharmacological approaches for future research in order to shed more light on the role of alterations in

neurotransmitter systems in time perception in clinical populations.

4.4. Limitations and recommendations for future research

A general issue for this meta-analysis was the heterogeneity of diagnostic criteria (DSM, ICD, Brief Psychiatric Rating Scale, etc.) and their modifications over time (e.g., DSM-II vs. DSM-III vs. DSM-IV). This factor might have led to inconsistencies in group assignment between the different studies. For instance, some subjects that were assigned to the control group in one study might have been classified as patients in another study that used different criteria for group assignment. A major difference between DSM-II and DSM-III had been the inclusion of a criterion of a minimum of 6 months of symptoms before schizophrenia was diagnosed. Accordingly, the DSM-II criteria were less restrictive and may have led to the inclusion of patients that would have been classified as healthy controls based on DSM-III. DSM-II criteria were used by one study only (Rutschmann, 1973). In this particular study, the effect size estimates for time reproduction and verbal time estimation were indeed relatively small. However, this single study does not permit to identify a potential confounding effect of diagnostic criteria. In general, the diagnostic criteria were more restrictive in Europe than in the USA. Considering the place where a particular study has been conducted (see Appendix Table A.2), there are, however, no indications that the effect size estimates are larger in those studies that were conducted in Europe. Based on these arguments, the fact that diagnostic criteria were inhomogeneous and modified over time does not appear to represent a serious limitation of our meta-analysis.

Besides analyzing the different studies based on the diagnostic criteria that have been used, it was not possible to systematically differentiate between different subtypes of schizophrenia or different phases of the pathology. For example, only one study (Schmidt et al., 2011) analyzed data separately for chronic and first episode schizophrenics, reporting no differences between subgroups in the impaired precision of temporal processing.

Another interesting methodological aspect concerns verbal time estimation tasks. As pointed out above, it is crucial to differentiate between prospective and retrospective judgments (cf. Grondin, 2010). This has not been done systematically in the context of schizophrenia yet. As pointed out in the introduction, in the prospective paradigm, the participant is informed about the temporal task and focuses attention on time. In the retrospective paradigm, the subject (being uninformed about the temporal task) does not focus attention on time. In contrast to prospective judgments, the task to give a retrospective estimate is less attention-related and more memory demanding (e.g., Brown, 2008; Grondin, 2010). There is evidence for systematic differences between prospective and retrospective time estimation (for a meta-analytic review see Block & Zakay, 1997), with prospective judgments being longer and less variable than retrospective judgments. Regarding possible effects of schizophrenia on time estimation, prospective and retrospective judgments might be affected differently, indicating whether attentional (prospective) processes or/and memory-related (retrospective) processes of time perception are altered in schizophrenia. Due to the fact that only few studies with verbal estimation tasks could be included in this meta-analysis, additional covariates, as for example the estimation paradigm (prospective vs. retrospective), could not be considered in the analysis. Inspection of the effect sizes (see Fig. 1) did not indicate substantial differences between results from studies including retrospective judgments (Oyanadel & Buela-Casal, 2014; Roy et al., 2012) and those including prospective judgments (Broadhurst, 1969; Johnson & Petzel, 1971; Rutschmann, 1973; Tracy et al., 1998). However, the two studies that actually tested both types of judgments within the same sample (Tysk, 1983b; Wahl & Sieg, 1980) reported somewhat larger effects (more overestimation in patients) in prospective relative to retrospective tasks. This pattern of results might indicate less memory – but rather attention-related impairments of time perception in patients – a result that corresponds to the larger within-subject variability (impaired precision) in patients. In order to systematically address this issue, future studies need to directly compare patients' performance in prospective versus retrospective time estimation tasks.

Unfortunately, our review revealed significant shortcomings in experimental design and statistical analysis in a relatively large number of original studies. Future studies should use the established psychophysical tasks for measuring time perception or temporal processing (cf. Grondin, 2008; Grondin, 2010), and analyze the data with adequate and established methods. For instance, data from one-interval discrimination tasks provide information about precision (in terms of the difference limen that can be estimated from the psychometric function), but also about accuracy (in terms of the 50% point on the psychometric function). This information is lost if the data are analyzed in terms of percent-correct rather than by fitting a psychometric function (cf. Treutwein & Strasburger, 1999), as explained in the introduction. As shown in Appendix Table A.1, of a total of four studies using one-interval duration discrimination tasks could not be included in the meta-analysis due to this issue. Another less severe issue concerns the analysis of data from two-interval discrimination tasks using a transformed up-down adaptive procedure (Levitt, 1971). Here, in most studies on effects of schizophrenia, the duration difference limen was computed as the average of the duration differences between comparison and standard interval across for example the last 20 trials (Rammsayer, 1990; Ulferts et al., 1999; Volz et al., 2001). The correct analysis is to compute the average duration differences between comparison and standard interval across for example the last six so-called reversals (Todd et al., 2000), which are trials on which the direction of the adaptive track changes (Levitt, 1971). If instead the average across trials is used, this results in a general overestimation of the duration difference limen.

Beyond applying the established tasks and procedures from the (general) time perception literature, future studies on time perception in schizophrenia may aim at addressing specific temporal distortions that are reported by patients. For example, time is described as passing by intermitted and non-continuous, as “running strangely” and “falling apart” (e.g., Martin et al., 2014). These impressions may not be captured adequately by the current experimental tasks. Future studies should therefore try to combine experimental and phenomenological approaches in order to gain a broader understanding of temporal distortions in schizophrenia and, more general, of the disease as such.

4.5. Conclusion

Taken together, the results of our meta-analysis indicate that the precision of time perception and temporal processing is substantially impaired in patients with schizophrenia. Thus, patients have a lower sensitivity in judging time intervals, and in more basic temporal tasks like temporal-order judgments. These effects of schizophrenia on precision do not significantly depend on the interval durations used, and do not differ substantially between tasks that are comprised of purely perceptual judgments and those requiring timed motor responses. In contrast, the accuracy of time perception in the sense of a systematic deviation of time estimates form the veridical value is not significantly affected by schizophrenia across the different tasks and duration ranges. However, it may depend on specific task-related cognitive demands (e.g., memory): A small to moderate effect in verbal time estimation and time production indicated an overestimation of duration in patients as compared to controls, while there was a reversed effect in temporal bisection tasks. Notwithstanding this qualification, the effect of schizophrenia on the accuracy of time perception is substantially smaller than the effect on precision.

Our review also shows that several aspects have not been investigated in sufficient detail yet and might be addressed by future research. These aspects include the role of specific task characteristics like prospective versus retrospective time estimation as well as potentially

mediating effects of medication and neurotransmitter levels. The effect sizes provided by our meta-analysis may be used for selecting appropriate sample sizes in future experiments. These studies should carefully differentiate between measures of mean duration estimates (accuracy) on the one hand and measures of variability (precision) on the other hand, and should aim at combining established experimental and phenomenological approaches in order to gain a broader understanding of the specific temporal distortions in schizophrenia.

Appendix A. Tables

Table A.1
Results of the literature search in alphabetical order. Studies were considered for further analyses only if all of the four inclusion criteria (see Introduction) were met.

Study	Empirical study?	Relevant tasks?	Patient and control group?	Data interpretable in terms of accuracy and/or precision?	Sufficient statistical information?	Authors' response in case of data request	Inclusion?
Allman and Meck (2012)	No (review)						No
Bolbecker et al. (2014)	Yes	Yes (duration discr.; temp. bisection)	Yes	Yes (A and P)	Yes		Yes
Bonnot and Georgieff (2000)	No (review)						No
Bonnot et al. (2011)	No (review)						No
Bourdet et al. (2003)	Yes	Yes (duration discr.; deviant detection)	Yes	No (duration DL defined by an unspecific performance level, range between 70 and 90% correct)	Yes		No
Braus (2002)	Yes	Yes (ToJ)	Yes (two groups of patients: medicated vs. unmedicated vs. control)	Yes (P)	Yes		Yes
Broadhurst (1969)	Yes	Yes (verbal time estimation)	Yes	Yes (A)	Yes		Yes
Capa et al. (2014)	Yes	Yes (ToJ; JoS)	Yes	Yes (P)	Yes (*F*-values and *N*s are reported)		Yes
Carlson and Feinberg (1968)	Yes	Yes (verbal time estimation; time production; time reproduction)	Yes	No (linear regression analysis of time estimates/productions across a wider range of intervals, thus not possible to distinguish between duration ranges to time intervals. No distinct measures of accuracy and precision.)	No (no tests of intercept and slope measures between groups)		No
Carroll et al. (2008)	Yes	Yes (duration discr.; temp. bisection)	Yes	Yes (A and P)	Yes		Yes
Carroll et al. (2009a)	Yes	Yes (continuation tapping)	Yes	Yes (A and P)	Yes		Yes
Carroll et al. (2009b)	Yes	Yes (temp. bisection)	Yes	Yes (A and P)	Yes		Yes
Clausen (1950)	Yes	Yes (verbal time estimation; time production; time reproduction)	No (no healthy control group; reported data: before and after removal of frontal lobes)	Yes (A)	No (no *SD*s or *F*/*t*-values reported)		No
Davalos et al. (2002)	Yes	Yes (duration discri.; one	Yes	No (only errors rates for each comparison interval	Yes	Data requested; no response	No

		interval reminder)		reported)			
Davalos, Kisley, and Ross (2003)	Yes	Yes (duration discri.; one interval reminder)	Yes	No (only error rates reported)	Yes	Data requested; no response	No
Davalos et al. (2005)	Yes	Yes (duration discri.; one interval reminder)	Yes	No (only error rates reported)	Yes	Data requested; no response	No
Davalos et al. (2011)	Yes	Yes (duration discri.; one interval reminder)	Yes	No (only error rates reported)	Yes	Data requested; no response	No
Delevoye-Turrell et al. (2012)	Yes	No (spontaneous finger tapping at preferred tempo)					No
Densen (1977)	Yes	Yes (verbal time estimation)	Yes	Yes (A)	No (no *SD*s or *F*/*t*-values reported)		No
Dilling and Rabin (1967)	Yes	Yes (verbal time estimation)	Yes	No (only frequency distributions of over- and underestimation reported)	No (only medians and sum of ranks reported)		No
Droit-Volet (2013)	No (review)						No
Elvevag et al. (2003)	Yes	Yes (duration discri.; temp. bisection)	Yes	Yes (A and P)	Yes		Yes
Elvevag, Brown, McCormack, Vousden, and Goldberg (2004)	Yes	Yes (duration discri.; absolute identification task with 7 durations)	Yes	No (only mean error rates reported)	Yes	Data requested but not received	No
Foucher et al. (2007)	Yes	Yes (JoS)	Yes	Yes (P)	Yes		Yes
Franck, Posada, Pichon, and Haggard (2005)	Yes	No ("timing judgment by Haggard")					No
Giersch et al. (2009)	Yes	Yes (JoS)	Yes	Yes (P)	Yes		Yes
Grondin, Pouthas, Samson, and Roy (2006)	No (review)						No
Jirsa et al. (1996)	Yes	No (40 Hz quanta synchronization finger tapping)					No
Johnson and Petzel (1971)	Yes	Yes (verbal time estimation; time production)	Yes	Yes (A)	Yes		Yes
Lalanne et al. (2012)	Yes	Yes (JoS)	Yes	Yes (P)	Yes		Yes
Lee et al. (2006)	Yes	Yes (duration discri.; temp. bisection)	No (schizotypy as continuous variable)				No
Lee et al. (2009)	Yes	Yes (duration discri.; temp. bisection)	Yes	Yes (A and P)	Yes		Yes
Lhamon and	Yes	Yes (duration	Yes	Yes (A and P)	Yes		Yes

Goldstone (1956)		discri.; temp. bisection)					
Lhamon and Goldstone (1973) Exp. 1 and 2	Yes	Yes (duration discri.; temp. bisection; one interval reminder)	Yes	Yes (P)	Yes		Yes
Martin et al. (2013)	Yes	Yes (JoS)	Yes	No (data were only partially reported in terms of P and A)	Yes	Data requested and received, but only data from 50% of the subjects were analyzed in a way appropriate for our analyses	No
Martin et al. (2014)	No (review)						No
Martinez-Cascales, de la Fuente, Santiago, and Santiago (2013)	Yes (conference contribution)				No (missing statistics)		No
Meck (2005)	No (review)						No
Mishara and Gallistel (2005)	Yes (conference contribution)	No					No
Nenadic et al. (2000)	Yes (conference contribution)	Yes (verbal time estimation)	Yes	No	No (no statistics, no behavioral results)		No
Nichols and Park (2011)	Yes (conference contribution)				No		No
Nosachev (1992)	Yes	Yes (time production)	Yes	Yes (A)	No (statistical measures not explained in the paper)		No
Orme (1966)	Yes	Yes (verbal time estimation)	Yes	Yes (A)	No (no means or *F*/*t*-values reported)		No
Oyanadel and Buela-Casal (2014)	Yes	Yes (verbal time estimation)	Yes	Yes (A)	Yes		Yes
Papageorgiou et al. (2013)	Yes	Yes (duration discri.; one interval reminder)	Yes	Yes (A and P)	No (no *SD*s or *F*/*t*-values reported)	Data requested but not received	No
Parsons et al. (2013)	Yes	No (flicker fusion)					No
Pearl and Berg (1963)	Yes	Yes (verbal time estimation)	No	Yes (A)	Yes		No
Penney et al. (2005)	Yes	Yes (duration discr.; temp. bisection)	Group of subjects at high genetic risk for schizophrenia vs. control group	Yes (A and P)	Yes		Yes
Peterburs, Nitsch, Miltner, and Straube (2013)	Yes	No (time to contact task estimation)					No
Rabin (1957)	Yes	Yes (verbal time estimation)	Yes	No (frequency distributions of	No		No

				categories of overestimation, under estimation and correct estimation)			
Rammsayer (1990)	Yes	Yes (duration discri.; two interval)	Yes	Yes (A and P)	Yes		Yes
Ratcliffe (2012)	No (review)						No
Roy et al. (2012)	Yes	Yes (verbal time estimation, time reproduction)	Yes	Yes (A and P)	Yes		Yes
Rutschmann (1973)	Yes	Yes (verbal time estimation, time reproduction)	Yes	Yes (A)	Yes		Yes
Schmidt et al. (2011)	Yes	Yes (JoS)	Yes (data from chronic vs. first episode patients vs. control group)	Yes (P)	Yes		Yes
Teixeira et al. (2013)	No (review)						No
Todd et al. (2000)	Yes	Yes (duration discri.; two interval)	Yes	Yes (P)	Yes		Yes
Todd et al. (2003)	Yes	Yes (duration discri.; two interval)	Yes	Yes (P)	No	Data requested, but not received	No
Tracy et al. (1998)	Yes	Yes (time reproduction)	Yes	Yes (A)	Yes		Yes
Turgeon et al. (2012)	Yes	Yes (duration discri.; deviant detection; time production)	Yes	Yes (A and P)	Yes		Yes
Tysk (1983a)	Yes (however, partially reported data from Tysk (1983b)						
Tysk (1983b)	Yes	Yes (verbal time estimation; time production)	Yes	Yes (A)	Yes		Yes
Ulferts et al. (1999)	Yes	Yes (duration discri.; two interval)	Yes (data from differently medicated groups of patients vs. control group)	Yes (P)	Yes		Yes
van der Veen et al. (2013)	Yes	Yes (time production)	Yes	No (only percentage of correct responses is reported)	Yes	Data requested and received, but not analyzable in terms of precision and/or accuracy	No
Volz et al. (2001)	Yes	Yes (duration discri. Two interval)	Yes	Yes (P)	Yes		Yes
Wahl and Sieg (1980)	Yes	Yes (verbal time estimation; time production)	Yes	Yes (A)	Yes		Yes
Waters and Jablensky (2009)	Yes	Yes (duration discri. Two interval)	Yes (patients with first rank symptoms vs. patients without first rank symptoms vs.	Yes (P)	Yes		Yes

		control group)			
Yang et al. (2004)	Yes	Yes (finger tapping)	No		No

Note. ToJ = Temporal-order judgment; JoS = Judgment of simultaneity. Studies excluded from the meta-analysis are indicated by grey ink.

Table A.2
Diagnostic criteria and demographic information on patients and control subjects as well as information on the place where the study has been conducted, covered tasks, dependent measures, modality, and presented interval durations for each study included in the meta-analysis.

Study, place	Diagnostics	Schizophrenics					Controls					Task	Accuracy measure	Precision measure	Modality	Interval duration (range)
		Age		Gender			Age		Gender							
		M	*SD*	N_{Ma}	N_{Fe}	*N*	*M*	*SD*	*N* Ma	*N* Fe	*N*					
Bolbecker et al. (2014), USA	DSM-IV			41	25	66			29	44	73	Duration discrimi. (temp. bisection)	BP	DL	Auditory	< 1 s; u-short
Braus (2002), Germany	Not specified[a]	34.9	9.1	21	14	35	31.4	8.1	13	13	26	*ToJ*		*SOA at 75% correct*	*Auditory; visual*	
Broadhurst (1969), UK	Not specified	39.6	12.1	24	0	24	33.5	10.0	24	0	24	Verbal estim. (p)	Signed error		Not specified	5 min; medium
Capa et al. (2014), France	DSM-IV	37.2	9.2	14	6	20	33.4	11.4	14	6	20	*ToJ*		*SOA at 75% correct*	*Visual*	
Carroll et al. (2008), USA	DSM-IV	39.7	11.0	15	8	23	41.1	12.1	6	16	22	Duration discrimi. (temp. bisection)	BP	WR [DL/BP]	Auditory; visual	< 1 s u-short
Carroll et al. (2009a), USA	DSM-IV	39.1	10.4	22	10	32	40.1	11.2	9	22	31	Time Reprod. [Finger Tapping (contin.)]	Inter tapping interval (Signed error)	CV of inter tapping interval	Auditory	< 1 s; u-short
Carroll et al. (2009b), USA	DSM-IV	39.1	10.2	21	7	28	39.5	10.5	11	20	31	Duration discrimi. (temp. bisection)	BP	WR [DL/BP]	Auditory; visual	< 1 s u-short
Elvevag et al. (2003), UK	DSM-IV	32.8	8.4	15	4	19	29.4	11.5	6	17	23	Duration discrimi.; (temp. bisection)	BP	WR [DL/BP]	Auditory; visual	< 1 s; u-short 4.5 s; short
Foucher et al. (2007), France	DSM-IV	33.0	9.0	21	9	30	32.0	11.0	22	11	33	*JoS*		*Inter stimulus interval at 50% 'sim.' –responses*	*Auditory; visual*	
Giersch et al. (2009), France	DSM-IV	30.6	6.1	13	6	19	30.1	6.7	13	6	19	*JoS*		*Inter stimulus interval at 50% 'sim.' –responses*	*Visual*	
Johnson and Petzel (1971), USA	Not specified	48.4		20	20	40	46.5		20	20	40		Signed error Signed error		Not specified Not specified	30 s; medium 30 s; medium
Lalanne et al. (2012), France	DSM-IV	35.7	6.3	9	9	18	34.3	6.4	9	9	18	*JoS*		*Inter stimulus interval at 50% 'sim.' –responses*	*visual*	
Lee et al.	DSM-IV	37.3	10.4	34	4	38	35.5	10.7	34	4	38	Duration	BP	DL	Auditory	~1 s;

(2009), UK											discrimi. (temp. bisection)				short
Lhamon and Goldstone (1956), USA	Not specified	33		34	3	37	27.0		31	10	41	Duration discrimi. (temp. bisection)	BP		Auditory	1 s; short
Lhamon and Goldstone (1973) Exp.1, USA	Not specified			160	0	160			103	57	160	Duration discrimi. (temp. bisection)		'Trans-mitted in-formation"	Auditory; visual	1 s; short
Lhamon and Goldstone (1973) Exp.2, USA	Not specified			17	13	30			17	13	30	Duration Discrimi. (one interval reminder)		'Trans-mitted in-formation"	Auditory; visual	1 s; short
Oyanadel and Buela-Casal (2014), Spain	DSM-IV	40.6	10.6	19	11	30	35.5	9.6	38	22	60	Time production	Signed error		NA	35 s; medium
												Verbal Estim. (r)	Signed error		NA	35 s; medium
Penney et al. (2005), USA	None (HrSz)	25.5	2.1	12	5	17	25.9	2.2	20	14	34	Duration Discrimi. (temp. bisection)	BP	DL	Auditory; visual	4.5 s; short
Rammsayer (1990), Germany	DSM-III	31.5	13.2	14	13	27	31.4	10.9	36	44	80	Duration Discrimi. (two interval, adaptive)		DL	Auditory	< 1 s; short
Roy et al. (2012), Canada	DSM-IV	25.7	6.3	24	1	25	25.7	4.3	24	1	25	Time reprod.		CV	Auditory	1.6 s; short
												Verbal Estim. (r)	Signed error		NA	~40 min; large
Rutschmann (1973), Germany	DSM-II	21.2	2.4	7	0	7	23.8	0.8	9	0	9	Time reprod.	Signed error		Auditory	1.3 s; short
												Verbal estim. (p)	Signed error			1.3 s; short
Schmidt et al. (2011), UK	DSM-IV	29.9	8.6	12	8	20	28.8	8.9	9	2	11	*JoS*		*Inter stimulus interval at 50% 'sim.' –responses*	*Visual*	
Todd et al. (2000), Australia	ICD-10; DSM-IV	28.3		15	2	17	26.6		18	2	20	Duration Discrimi. (two interval, adaptive)		DL	Auditory	< 1 s; u-short
Tracy et al. (1998), USA	DSM-III	47.3	10.1	9	10	19	26.6	11.0	14	29	43	Verbal Estim. (p)	Abs. error and signed error		Not specified	24 s; medium
												Time Production	Abs. error and signed error		NA	24 s; medium
Turgeon et al. (2012), UK	DSM-V	39.2	9.3	14	6	20	39.2	14.0	12	8	20	Time production	Signed error	DL	NA	< 1 s; u-short
												Duration discrimi. (deviant detection)			Auditory	< 1 s; u-short
Tysk (1983a), Sweden	DSM-III	34.8	11.1	30	20	50	37.6	10.6	26.	34	60	Time production	Signed error		Not specified	20 s; medium
												Verbal estim. (p)	Signed error		Not specified	17.5 s; medium

															NA	7.5 min; medium
Ulferts et al. (1999), Germany	ICD-9	31.0	7.2	21	15	36	28.1	4.6	7	5	12	Duration discrimi. (two interval, adaptive)		DL	Auditory	< 1 s; u-short
Volz et al. (2001), Germany	DSM-IV; ICD-10	31.7	12.1	9	0	9	25.3	3.6	15	0	15	Duration discrimi. (two interval, adaptive)		DL	Auditory	1 s; short
Wahl and Sieg (1980), Germany	Not specified			12	14	26			19	7	26	Time Production	Signed error		NA	30 s; medium
												Verbal Estim. (p)	Signed error		Not specified	30 s; medium
												Verbal Estim. (r)	Signed error		NA	~30 min; large
Waters and Jablensky (2009), Australia	DSM-IV; ICD-10	34.8	9.3	35	0	35	44.0	9.9	16	0	16	Duration Discrimi. (one interval reminder)		*d′*	auditory	1.2 s; short

Note. Empty cells represent missing information in studies. Data in quotation marks refer to statements from the studies. Estim. = Estimation; (r) = retrospective; (p) = prospective; Reprod. = Reproduction; Discrimi = Discrimination; Ma = male; Fe = Female; *M* = Mean; *SD* = Standard deviation; *N* = sample size; DM = Dependent measure; HrSz: Subjects with high genetic risk for schizophrenia (offspring of patients diagnosed with schizophrenia); Temp. = Temporal; BP = Bisection point (Point of subjective equality); DL = Difference limen; WR = Weber ratio; CV = Coefficient of variation; contin. = continuation; abs. = absolute; SI = Standard interval; corr. resp. = Correct responses; *ToJ* = *Temporal-order judgment*; *JoS* = *Judgment of simultaneity*; NA = not applicable; *Italics* indicate tasks and measures referring to *temporal processing*; "Interval duration" is not definable for temporal processing tasks.
[a] In the study by Braus (2002), an average score of 45.6 on the Brief Psychiatric Rating Scale was reported for the patients with schizophrenia.

Table A.3
Averaged effect sizes (*g*), effect size variances (Var(*g*)), corresponding 95% confidence intervals (CI_{lower} and CI_{upper}), and number of reported means (*J*) per combination of sample and task. *J* denotes the number of effects sizes on which the averaged *g* is based on.

Study	Task	*J*	*g*	Var(*g*)	CI_{lower}	CI_{upper}
	Accuracy in time perception					
Rutschmann (1973)	Verbal estimation	7	− 0.369	0.258	− 1.365	0.627
Tracy et al. (1998)	Verbal estimation	2	− 0.224	0.150	− 0.983	0.535
Oyanadel and Buela-Casal (2014)	Verbal estimation	1	− 0.070	0.050	− 0.508	0.368
Wahl and Sieg (1980)	Verbal estimation	2	0.459	0.079	− 0.092	1.010
Johnson and Petzel (1971)	Verbal estimation	1	0.478	0.051	0.035	0.921
Roy et al. (2012)	Verbal estimation	1	0.721	0.091	0.130	1.312
Tysk (1983a)	Verbal estimation	4	0.726	0.039	0.339	1.113
Broadhurst (1969)	Verbal estimation	2	0.965	0.093	0.367	1.563
Oyanadel and Buela-Casal (2014)	Time production	2	− 0.276	0.050	− 0.714	0.162
Turgeon et al. (2012)	Time production	1	0.032	0.100	− 0.588	0.652
Tracy et al. (1998)	Time production	2	0.155	0.149	− 0.602	0.912
Tysk (1983a)	Time production	3	0.849	0.040	0.457	1.241
Johnson and Petzel (1971)	Time production	1	0.856	0.055	0.396	1.316
Wahl and Sieg (1980)	Time production	1	1.540	0.100	0.920	2.160
Rutschmann (1973)	Time reproduction	7	− 0.076	0.254	− 1.064	0.912
Carroll et al. (2009a)	Time reproduction	1	1.024	0.072	0.498	1.550
Bolbecker et al. (2014)	Temporal bisection	1	− 1.172	0.034	− 1.533	− 0.811
Penney et al. (2005)	Temporal bisection	2	− 0.966	0.097	− 1.576	− 0.356
Elvevag et al. (2003)	Temporal bisection	1	− 0.843	0.105	− 1.478	− 0.208
Lee et al. (2009)	Temporal bisection	2	− 0.453	0.054	− 0.908	0.002
Carroll et al. (2008)	Temporal bisection	2	0.246	0.090	− 0.342	0.834
Carroll et al. (2009b)	Temporal bisection	2	0.261	0.069	− 0.254	0.776
Lhamon and Goldstone (1956)	Temporal bisection	2	0.721	0.055	0.261	1.181
Precision in time perception						
Bolbecker et al. (2014)	Temporal bisection	1	− 5.952	0.156	− 6.730	− 5.178
Penney et al. (2005)	Temporal bisection	2	− 2.828	0.166	− 3.627	− 2.029
Volz et al. (2001)	Two interval	1	− 2.036	0.264	− 3.043	− 1.029
Turgeon et al. (2012)	Temp. deviant detec.	1	− 1.994	0.150	− 2.753	− 1.235
Lhamon and Goldstone (1973), Expt. 2	One interv. reminder	1	− 1.517	0.086	− 2.092	− 0.942

Rammsayer (1990)	Two interval	1	− 1.406	0.059	− 1.882	− 0.930
Lhamon and Goldstone (1973), Expt. 1	Temporal bisection	1	− 1.118	0.014	− 1.350	− 0.886
Ulferts et al. (1999)	Two interval	2	− 0.936	0.120	− 1.615	− 0.257
Waters and Jablensky (2009)	One interv. reminder	1	− 0.763	0.100	− 1.383	− 0.143
Lee et al. (2009)	Temporal bisection	2	− 0.697	0.056	− 1.161	− 0.233
Todd et al. (2000)	Two interval	1	− 0.675	0.115	− 1.340	− 0.010
Elvevag et al. (2003)	Temporal bisection	1	− 0.639	0.101	− 1.262	− 0.016
Carroll et al. (2009b)	Temporal bisection	2	− 0.631	0.071	− 1.153	− 0.109
Carroll et al. (2008)	Temporal bisection	2	− 0.312	0.090	− 0.900	0.276
Carroll et al. (2009a)	Time reproduction	1	− 1.238	0.076	− 1.778	− 0.698
Roy et al. (2012)	Time reproduction	3	− 0.394	0.087	− 0.972	0.184
Precision in temporal processing						
Schmidt et al. (2011)	Simultaneity judg.	1	− 2.002	0.206	− 2.892	− 1.112
Giersch et al. (2009)	Simultaneity judg.	1	− 0.919	0.116	− 1.587	− 0.251
Capa et al. (2014)	Simultaneity judg.	1	− 0.834	0.109	− 1.481	− 0.187
Foucher et al. (2007)	Simultaneity judg.	3	− 0.812	0.069	− 1.327	− 0.297
Lalanne et al. (2012)	Simultaneity judg.	1	− 0.751	0.119	− 1.427	− 0.075
Braus (2002)	Temporal-order judg.	2	− 1.330	0.082	− 1.891	− 0.769
Capa et al. (2014)	Temporal-order judg.	1	− 0.801	0.108	− 1.445	− 0.157

Note. In the analysis, continuation tapping has been regarded as time reproduction. Two interval, temporal bisection, one interval reminder tasks, and temporal deviant detection are grouped as duration discrimination tasks in the main analyses. Temporal bisection is the only duration discrimination task that provides information on accuracy of time perception (bisection point). Outlying data are indicated by grey ink.

Table A.4
Averaged effect sizes (g), effect size variances (Var(g)), corresponding 95% confidence intervals (CI_{lower} and CI_{upper}), and number of reported means (J) per combination of sample and interval range. J denotes the number of effects sizes on which the averaged g is based on.

Study	Interval range	J	g	Var(g)	CI_{lower}	CI_{upper}
	Accuracy in time perception					
Oyanadel and Buela-Casal (2014)	Long	1	− 0.070	0.050	− 0.509	0.368
Wahl and Sieg (1980)	Long	1	0.200	0.077	− 0.345	0.745
Roy et al. (2012)	Long	1	0.721	0.091	0.131	1.312
Oyanadel and Buela-Casal (2014)	Medium	2	− 0.276	0.050	− 0.714	0.162
Tracy et al. (1998)	Medium	4	− 0.034	0.148	− 0.788	0.720
Johnson and Petzel (1971)	Medium	2	0.667	0.053	0.216	1.118
Tysk (1983a)	Medium	6	0.781	0.039	0.394	1.168
Broadhurst (1969)	Medium	2	0.965	0.093	0.367	1.563
Wahl and Sieg (1980)	Medium	2	1.129	0.089	0.544	1.714
Penney et al. (2005)	Short	2	− 0.966	0.097	− 1.576	− 0.356
Lee et al. (2009)	Short	1	− 0.234	0.053	− 0.685	0.218
Rutschmann (1973)	Short	10	− 0.193	0.255	− 1.183	0.797
Carroll et al. (2009b)	Short	1	0.243	0.068	− 0.270	0.756
Lhamon and Goldstone (1956)	Short	2	0.721	0.055	0.261	1.182
Tysk (1983a)	Short	1	0.768	0.039	0.379	1.157
Bolbecker et al. (2014)	Ultra-short	1	− 1.172	0.034	− 1.532	− 0.812
Elvevag et al. (2003)	Ultra-short	1	− 0.843	0.105	− 1.477	− 0.209
Lee et al. (2009)	Ultra-short	1	− 0.672	0.056	− 1.134	− 0.210
Rutschmann (1973)	Ultra-short	4	− 0.296	0.257	− 1.289	0.698
Turgeon et al. (2012)	Ultra-short	1	0.032	0.100	− 0.587	0.652
Carroll et al. (2008)	Ultra-short	2	0.246	0.090	− 0.342	0.834
Carroll et al. (2009b)	Ultra-short	1	0.278	0.069	− 0.236	0.791
Carroll et al. (2009a)	Ultra-short	1	1.024	0.072	0.499	1.549
Precision in time perception						
Bolbecker et al. (2014)	Ultra-short	1	− 5.952	0.156	− 6.727	− 5.178
Carroll et al. (2008)	Ultra-short	2	− 0.312	0.090	− 0.900	0.276
Carroll et al. (2009b)	Short	1	− 0.668	0.072	− 1.193	− 0.143
Carroll et al. (2009b)	Ultra-short	1	− 0.594	0.071	− 1.116	− 0.072
Carroll et al. (2009a)	Ultra-short	1	− 1.238	0.076	− 1.777	− 0.699
Elvevag et al. (2003)	Ultra-short	1	− 0.639	0.101	− 1.261	− 0.016
Lee et al. (2009)	Short	1	− 0.733	0.056	− 1.197	− 0.268
Lee et al. (2009)	Ultra-short	1	− 0.660	0.056	− 1.122	− 0.199
Lhamon and Goldstone (1973), Expt. 1	Short	1	− 1.118	0.014	− 1.354	− 0.883
Lhamon and Goldstone (1973), Expt. 2	Short	1	− 1.517	0.086	− 2.091	− 0.942
Penney et al. (2005)	Short	2	− 2.828	0.167	− 3.629	− 2.027

Rammsayer (1990)	Ultra-short	1	− 1.406	0.059	− 1.881	− 0.931
Roy et al. (2012)	Short	2	− 0.466	0.088	− 1.046	0.113
Roy et al. (2012)	Ultra-short	1	− 0.250	0.086	− 0.824	0.324
Todd et al. (2000)	Ultra-short	1	− 0.675	0.115	− 1.339	− 0.010
Turgeon et al. (2012)	Ultra-short	1	− 1.994	0.150	− 2.752	− 1.235
Ulferts et al. (1999)	Short	1	− 1.032	0.122	− 1.717	− 0.346
Ulferts et al. (1999)	Ultra-short	1	− 0.841	0.118	− 1.516	− 0.166
Volz et al. (2001)	Short	1	− 2.036	0.264	− 3.043	− 1.029
Waters and Jablensky (2009)	Short	1	− 0.763	0.100	− 1.382	− 0.144

Note. In the analysis, continuation tapping has been regarded as time reproduction. Two interval, temporal bisection, one interval reminder tasks, and temporal deviant detection are grouped as duration discrimination tasks in the main analyses. Temporal bisection is the only duration discrimination task that provides information on accuracy of time perception (bisection point). Outlying data are indicated by grey ink.

Appendix B. Equations

$$g = \frac{M_d - M_c}{S} \tag{B.1}$$

$$s = \sqrt{\frac{(n_d - 1)SD_d^2 + (n_c - 1)SD_c^2}{n_d + n_c - 2}} \tag{B.2}$$

$$g = \sqrt{F\frac{n_d + n_c}{n_d n_c}\frac{n_d + n_c}{n_d + n_c - 2}} \tag{B.3}$$

$$g = t\sqrt{\frac{n_d + n_c}{n_d n_c}\frac{n_d + n_c}{n_d + n_c - 2}} \tag{B.4}$$

$$Var(g) = \frac{n_d + n_c}{n_d n_c} + \frac{g^2}{2(n_d + n_c)} \tag{B.5}$$

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