Speed or duration? Effects of implicit stimulus attributes on perceived duration

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ABSTRACT
The human ability to keep track of time can be distorted by several non-temporal stimulus aspects such as size or intensity. First studies indicate that not only physical but also implicit stimulus aspects can affect duration estimates. The present study expands these findings by investigating the effects of linguistic expressions including speed and duration information via temporal reproduction (Experiments 1 and 2) and temporal bisection tasks (Experiment 3). In Experiment 1, implicit duration was manipulated by combining verbs that denote slow or fast motion with a path expression (to stroll to school vs. to spurt to school). Reproduced durations were consistent with an effect of implicit duration but not implicit speed. To control whether implicit speed affects perceived duration when exempted from duration information, single manner of motion verbs were presented in Experiments 2 and 3. The results speak against an effect of implicit speed analogous to physical speed.

1. Introduction
Tracing the duration of temporal intervals is an everyday human ability and essential for an organism (Matthews & Meck, 2016; Núñez et al., 2012; Wittmann, 2009). Even though there is no dedicated sense organ for time, humans show stable temporal judgment behaviour such as scalar timing and scale invariance, which speaks for the existence of a specific but yet to be fully understood process that is responsible for the mental representation of physical time (Matthews & Meck, 2016). For instance, in temporal reproduction tasks in which participants are presented with a particular duration and are asked to produce an interval of the same extent, they quite accurately reproduce time intervals up to approximately 3 s (Daikoku et al., 2018). Interestingly, however, various non-temporal aspects of the sensory input affect subjective time, such as stimulus magnitude, intensity, or complexity (Allman et al., 2014; Matthews & Meck, 2016; Wang & Gennari, 2019). A prominent explanation for this phenomenon is the interference of non-temporal stimulus properties with different components of the internal clock (for details on the internal clock model, see Allman et al., 2014; Matthews & Meck, 2016).

Moreover, recent studies have shown that not only physical but also implicit or imagined stimulus aspects affect duration estimates (Birngruber & Ulrich, 2019; Bottini & Casasanto, 2010; Ma et al., 2012). For example, in the study by Birngruber and Ulrich (2019), participants’ reproduced durations (RD) were influenced by the imagined size of an animal word’s referent. Specifically, participants tended to judge the duration of words longer when the word’s referent was a large animal compared to a small one (for an effect of implicit weight and volume, see Ma et al., 2012; for an effect of implied motion, see Yamamoto & Miura, 2012). These findings of analogous effects of mentally imagined to physically present stimulus aspects on perceived durations corroborate the notion that perception and imagination draw on
the same brain circuits to establish a depictive representation of the perceived or imagined stimulus (Birngruber & Ulrich, 2019; Moulton & Kosslyn, 2009; Pearson & Kosslyn, 2015). The present study aims to extend this research and investigates whether dynamic mental images that are induced by linguistic expressions containing manner of motion verbs with different levels of associated speed can affect perceived duration. Against this background, the aim of Experiment 1 was to determine how speed and duration information as implicit stimulus aspects of complex expressions interact and how they contribute to a potential effect on reproduced durations. Experiment 2 was designed to disentangle speed from duration information, again implementing a duration reproduction task. Due to conflicting results with a temporal bisection study by Zhang et al. (2014), Experiment 3 was conducted as a replication of Zhang et al. (2014) to gain a better understanding of the effect of linguistically expressed speed information on perceived duration.

Besides these issues on temporal perception, this research relates to the grounded cognition debate which deals with the question of how and to what extent cognition – including language processing – relies on multimodal representations that come into play via simulations. Such simulations are framed as “the reenactment of perceptual, motor, and introspective states acquired during experience with the world, body, and mind” (Barsalou, 2008, p. 618). Thus, if participants simulate the meaning of expressions that are presented during an interval whose duration has to be estimated, i.e. if the meaning of those expressions were grounded in sensomotoric brain areas in which also the analog physical stimulus is processed, the expressions’ denotations should affect perceived duration similar to their physical counterparts.

Physical speed as a function of distance per time unit has been shown to lead to an overestimation of duration (Brown, 1995; Kanai et al., 2006; Kaneko & Murakami, 2009; Karşılar et al., 2018; Linares & Gorea, 2015; Tomassini et al., 2011; van Rijn, 2014). For instance, Brown (1995) found that higher velocity is perceived to last longer than lower velocity in both duration reproduction and production tasks, using stimulus durations in the supra-second time range, which will in the following be referred to as the dilation effect of physical speed (DEPS). Kanai et al. (2006) replicated Brown’s findings for sub-second stimulus durations. In addition, Tomassini et al.’s (2011) data imply that the DEPS not only applies to visual stimuli but also to the tactile modality. Moreover, Karşılar et al. (2018) replicated the DEPS for biological motion via the visual presentation of an animated, walking stick-figure. Furthermore, the effect has not only been observed for perceived motion but also for self-conducted motion: Time subjectively dilates with an increase in higher running intensity or, more specifically, with an increase in higher ratings of perceived exertion (RPE) in treadmill runs (Hanson & Lee, 2020). Analogous to what has been observed for physical and implicit size, the temporal bisection study by Zhang et al. (2014) indicates that implicit speed acts on perceived duration just like physical speed: the presentation duration of fast-speed verbs and adjectives (e.g. gallop) was overestimated compared to that of slow-speed verbs and adjectives (e.g. limp), suggesting a dilation effect of implicit speed (DEIS). Thus, an increase in visually, motorically, or tactually perceived speed has been shown to lead to an overestimation of perceived duration which applies to both biological and non-biological motion, and ostensibly also to linguistically encoded speed information, supporting a grounded cognition view on the processing of linguistically expressed speed information.

The dilation effect of both physical and implicit speed can be explained with an information-processing account, which assumes that the duration of an interval is estimated through the number of changes present in a stimulus (Karsilar et al. 2018). Thus, fast motion should be perceived to take longer compared to slow motion since it involves more changes of position in the same unit of time (Kanai et al., 2006). Alternatively, a higher level of arousal when processing fast compared to slow speed might increase the pacemaker rate, which would lead to a larger amount of pulses being counted and to a consequential dilation of perceived duration for fast compared to slow motion (Behm & Carter, 2020; Karşılar et al., 2018; Zhang et al., 2014).

In Experiment 1 of the present study, participants were asked to reproduce the presentation duration of expressions such as to stroll to school as opposed to to spurt to school, for which they were also told to form mental images. Verb phrases containing a motion verb denoting either fast (e.g. to spurt; in the following referred to as fast-speed verbs) or slow locomotion (e.g. to stroll; in the following referred to as slow-speed verbs) in combination
with a prepositional phrase denoting a path (e.g. to school; in the following referred to as path PP) provide the reader with two stimulus aspects. On the one hand, the reader obtains duration information (i.e. fast motion on a given path takes shorter than slow motion on the same path), while on the other hand, the expressions contain the highly salient feature of speed as distinctive property. There are two alternative scenarios for the build-up of the corresponding mental images that the participants were asked to form. Firstly, all items of the expression might be taken into account compositionally to establish a dynamic representation of the described event (Pearson & Kosslyn, 2015). When keeping the path information constant as in these sentences, expressions with slow-speed verbs denote longer events than expressions with fast-speed verbs. We conjecture that this difference in the events’ durations could affect the perceived duration. More precisely, the encoding of these expressions’ presentation duration in reference memory for later retrieval in the decisional process might be biased by the duration of the linguistically expressed events. As subjective time increases with physical time (Allman et al., 2014), the perceived duration should be longer for sentences with slow-speed rather than fast-speed verbs.

Alternatively, the mental image might mainly consist of the visual or motoric simulation of the kinematics denoted by the manner of motion verbs. This could be due to the high salience of motion in these expressions and its potential behavioural importance (Matthews & Meck, 2016). During the imagination of the presented expressions, the expressed action might thus overshadow the expressed events’ duration. Consequently, an effect of speed analogous to its physical counterpart should be expected, that is, an overestimation of the presentation duration of fast-speed compared to slow-speed verbs (Zhang et al., 2014), which is thus in contrast to the prediction of the compositional account mentioned in the preceding paragraph.

The design and predictions of Experiments 2 and 3, which investigate the effect of isolated speed information in manner of motion verbs on perceived duration, will be derived in the course of discussion.

2. Experiment 1

Experiment 1 was designed to distinguish empirically between the two hypotheses established above, that is, the compositional account as opposed to the salience of motion account. For this purpose, expressions such as those mentioned above (to stroll to school vs. to spurt to school) were presented for varying time intervals, and participants were asked to imagine the expressions’ denotation and then reproduce the duration of the expressions’ physical appearance on the screen. If the speed information was taken into account compositionally in the dynamic mental image, RDs of expressions with fast-speed verbs should be shorter than RDs of expressions with slow-speed verbs due to the duration of the linguistically denoted events. If, however, the mental image was mainly driven by the sensomotoric simulation of the denoted manner of motion with shallow processing of the path information, RDs of expressions with fast-speed verbs are expected to be longer than RDs of expressions with slow-speed verbs. This is derived from the effect of physical speed on perceived duration. The experiment was preregistered on the Open Science Framework (von Sobbe et al., 2019a).

2.1. Method

2.1.1. Participants

Sixty students of the University of Tübingen took part in the experiment and received either payment or course credit for their participation. Their age ranged from 19 to 65 (M = 25.28 years) and they were native speakers of German. Due to a predefined exclusion criterion (see the Procedure and Results Sections for details), 22 participants’ data had to be replaced. Additionally, one person accidentally participated twice, so her second data set was also replaced. All participants gave written informed consent.

2.1.2. Apparatus and stimuli

The experiment was programmed in PsychoPy v1.90.3 and presented on two Windows PCs (60 and 100 Hz refresh rate). The arrow down key of a standard German keyboard was used to measure the reproduced duration.

The stimulus material was built upon thirty German manner of motion verbs denoting either fast or slow human locomotion. The verbs were paired according to a speed rating that was conducted with an independent sample of 40 participants (see Table 1 for the verb pairings, and Appendix A for details on the speed rating study).
Each verb pair, for instance, *bummeln* (to stroll) and *spurten* (to spurt) was then combined with three different prepositional phrases that denoted a path, on which the motion was carried out (see (1) to (3)). To minimise the length of the expression, no agent was included and the verbs were in infinitive.

(1a) durchs Museum bummeln (to stroll through the museum)
(1b) durchs Museum spurten (to spurt through the museum)
(2a) zur Schule bummeln (to stroll to school)
(2b) zur Schule spurten (to spurt to school)
(3a) zur Haltestelle bummeln (to stroll to the station)
(3b) zur Haltestelle spurten (to spurt to the station)

To evoke a difference in duration via the motion verbs’ speed, the imagination of the same path within each item was necessary. For instance, people should imagine the same path when reading *to stroll to school* as when reading *to spurt to school*. For this purpose, a matching photo of a path was selected for each path PP and presented prior to the duration reproduction task (see Figure 1 and the Procedure Section for details).

Since the stimulus material was based on fifteen verb pairs that were repeated with three different path PPs each, the stimulus material contained 45 distinct path PPs and matching photos. These were considered items in the statistical analysis (see Supplemental Material for a list of all stimuli). The expressions were split into three lists such that each list contained all 15 verb pairs, that is, all 30 manner of motion verbs.

Ten additional motion verbs with one path PP each (*springen*, *fallen*, *galoppieren*, *traben*, *schippern*, *segeln*, *fahren*, *düsen*, *brettern*, and *tuckern*) were used for the practice block. All stimuli were presented in white colour against a grey background (Arial; scaling factor 0.07).

### 2.1.3. Procedure

The experiment was run in a sound-attenuated room. One experimental session lasted about 40 min. A session consisted of one practice block, three experimental blocks and a subsequent...
memory task (see Figure 1 for the time course of an experimental session).

Participants were given written instructions prior to the start of the experiment. They were asked to mentally imagine the expressions while performing the duration reproduction task. The necessity to engage with mental imagination was constituted by informing the participants about a memory task that would follow the main experiment. They were told that they would have to recall the verb-path-combinations in the memory task and that vividly imagining the verbs’ implied motion along the respective path would help them to perform well in it (Birngruber & Ulrich, 2019). Moreover, participants were instructed to attentively look at the pictures presented prior to the duration reproduction task. They were told that they would have to recall the verb-path-combinations in the memory task and that vividly imagining the verbs’ implied motion along the respective path would help them to perform well in it (Birngruber & Ulrich, 2019). Moreover, participants were instructed to attentively look at the pictures presented prior to the duration reproduction task. They were asked to memorise the pictures in combination with their subtitle, that is, the path PP, and were told that these path expressions would reappear in the subsequent duration reproduction task. The pictures would help them to mentally imagine the expressions that would appear in the later task.

The practice block consisted of an initial presentation of five pictures and 20 subsequent trials of the duration reproduction task. The experimental blocks each consisted of 15 pictures and 60 duration reproduction trials (see Figure 1). Each trial of the duration reproduction task started with a blank screen of either 1.8 or 2.4 s. In order to prevent rhythmic response patterns, these two intertrial intervals (ITI) were presented in randomised order (ITI design adopted from Rammsayer & Verner, 2015). Subsequently, the stimulus expression was presented for either 1050 or 1300 ms. These two stimulus durations were employed to ensure that participants were following task instructions and were able to distinguish between the two different stimulus durations. If this was not the case, that is, if the mean RDs of a participant did not increase with stimulus duration, the participant’s whole data set was excluded (Birngruber & Ulrich, 2019). The order of stimulus presentation was randomised for each participant. The target stimulus was then replaced by a blank screen with a fixed interstimulus interval (ISI) of 1.2 s after which a white cross appeared at the centre of the
screen. The RD started with the appearance of the cross. Participants were asked to press the “arrow down” key when they felt that the cross was presented as long as the target stimulus had been presented. As soon as they pressed the key, the next ITI started. Breaks were included after each block and after every 20 trials of one block. Participants could terminate the breaks via key press.

In each block, before the beginning of the duration reproduction task, the corresponding pictures that matched the path PPs of that block were presented for 6 s each. The path PP was written underneath the photo; for instance, the photo of a path to a school building was subtitled to school. Order of picture presentation was randomised for each participant. Picture presentation was followed by a screen, which informed the participants about the upcoming start of the duration reproduction task (presented for 4 s).

The 60 trials of the duration reproduction task in one experimental block were defined by the factorial combination of 30 expressions (i.e. 15 verb pairs in combination with a path PP) with two different presentation durations (1050 vs. 1300 ms). Each participant was presented with all three stimulus lists (one per block). List order was counterbalanced between participants.

In the memory task, the participants were presented with 32 expressions one after another. They had to indicate via keypress whether these were included in the duration reproduction task or not. Presentation order was randomised for each participant. Sixteen of the presented expressions were extracted from the experimental stimulus material. Eight expressions were expressions in which either the motion verb or the path PP was new and not part of the experimental stimulus material. A further eight expressions were false friends by combining actual verbs of the experimental stimulus material with actual path PPs of the experimental stimulus material but the specific verb-path-PP-combination was not contained in the experimental stimulus material.

2.2. Results

Outliers were excluded following a two-step procedure: All trials in which RDs exceeded 5000 ms or fell below 100 ms were excluded. Secondly, for each participant in each stimulus duration and each speed of motion verb condition, RDs that deviated by more than 2.5 standard deviations from the mean of the respective cell were considered outliers and excluded from further analysis. Overall, this led to an exclusion of 5.54% of the data.

Furthermore and according to the pre-defined exclusion criterion (see Procedure), a participants’ whole data set was excluded, if the mean RDs of the remaining data of that participant did not increase with stimulus duration. Due to this

![Figure 2. Mean reproduced durations in Experiment 1 as a function of Speed and Stimulus Duration. Note: Error bars represent 95% confidence intervals of the within-subject standard error (Morey, 2008).](image-url)
exclusion criterion, the data of twenty-two participants had to be excluded and were replaced. Mean RDs of the two levels of Speed per Stimulus Duration are plotted in Figure 2.

As preregistered, we analysed the remaining data with a linear mixed effects model (LME) using the lme4 package (Bates et al., 2015) in R (Version 4.0.3, 2020) to predict RD as a function of Stimulus Duration (1050 ms and 1300 ms; mean centred), Speed (fast and slow; with fast as reference category), and Number of Characters (mean centred). Number of Characters encodes physical size, which has been shown to affect perceived duration (Birngruber & Ulrich, 2019). Subjects and Items (i.e. path PPs), were considered random factors. Block was not considered as a fixed factor in the preregistration of the analysis, because there was no theoretical foundation for it. However, upon inspection of the data, a trend of longer reproduced durations along with the proceeding of the experiment was observable (Block 1: $M = 1499$ ms ($SD = 732$); Block 2: $M = 1592$ ms ($SD = 761$); Block 3: $M = 1632$ ms ($SD = 772$); see Figure 3 for mean RDs of all cells). We thus conducted a sensitivity analysis, which included Block as a fixed factor (see Appendix B for details). This did not alter the results of the preregistered analysis. Moreover, we assessed the effect of Frequency on RDs by including Frequency as a fixed factor in the LME (see Appendix C for details), which again did not alter the results of the preregistered main analysis.

The random-effects structure was determined by step-wise reducing the most complex random effects structure, while at the same time keeping the fixed effects structure constant (Barr et al., 2013). The Akaike information criterion (AIC) was used as an indicator for the random effects structure selection. The random-effects structure with the best AIC value included random intercepts for Subjects and Items (i.e. path PPs), and random slopes for the factor Speed for Subjects. This random effects structure did not only have the best AIC value, but additionally was the most complex random effects structure that converged and did not over-fit the data. This yielded the following full model: $RD \sim$ Stimulus Duration + Speed + Number of Characters + (Speed | Subjects) + (1 | Items).

$P$-values could not be obtained with $\chi^2$ difference tests on the full model in comparison with reduced models, since one of the reduced models did not converge. Consequently, $p$-values were obtained using the Satterthwaite’s approximation for degrees of freedom as suggested by Luke (2017) which is built-in in the summary method of the lmerTest function (Kuznetsova et al., 2017) in R (Version 4.0.3, 2020).

The full model suggests an intercept of $\beta = 1597.53$ ms. As expected, the estimated coefficient

Figure 3. Mean reproduced durations in Experiment 1 as a function of Speed and Stimulus Duration per Block and List. Note: Error bars represent 95% confidence intervals of the within-subject standard error (Morey, 2008).
of Stimulus Duration ($\beta = 587.39$, $SE = 35.86$, $t (10030.71) = 16.38$, $p < .001$) was significant, implying that perceived duration increases with physical duration. The estimated coefficient of Number of Characters was also significant ($\beta = 7.18$, $SE = 1.60$, $t (64.12) = 4.49$, $p < .001$) and comparable in size to that of previously estimated coefficients for the number of characters in duration reproduction tasks (7.06, 9.17, and 7.10 ms in the three experiments of Birngruber & Ulrich, 2019). Thus, we were able to replicate the effect of physical size on perceived durations. Interestingly – and theoretically most importantly – the estimated coefficient of Speed with reference category fast was positive and significant ($\beta = 94.74$ ms, $SE = 36.79$, $t(53.50) = 2.58$, $p = .013$), suggesting an increase in perceived duration of expressions with slow-speed verbs compared to expressions with fast-speed verbs.

The coefficient of variation (CV) was calculated for each participant, Stimulus Duration, and both levels of Speed by dividing the standard deviation by the mean of the respective cell. Mean CV for a Stimulus Duration of 1050 ms was 0.25 and mean CV for a Stimulus Duration of 1300 ms was 0.23, which is in accordance with the CV reported by Mioni et al. (2014, Figure 4, Method 1) for a Stimulus Duration of 1 s.

In the memory task, participants’ hit rate was 76.67%. The false alarm rate for false friends items was relatively high with 65.21%, while the false alarm rate for items that contained at least either a verb or a context that they had not seen before was much lower (9.58%). These results indicate that participants were doing well in distinguishing between experimental and new items while they were having problems with recalling the correct mappings of verbs and path PPs. Overall, however, the results imply that participants were paying attention to the experimental items.

2.3. Discussion

The duration of expressions with slow-speed verbs was reproduced longer than the duration of expressions with fast-speed verbs. This overestimation of expressions with slow-speed verbs implies that the speed information associated with the manner of motion verbs as well as the path on which the motion takes place is taken into account compositionally as part of the mental image of the expressions. Thus, RDs are modulated by the denoted events’ durations (i.e. fast motion on a given path takes shorter than slow motion on the same path), suggesting that subjective time increases not only with physical but also with implicit time. Consequently, in the expressions employed in the present experiment in which both speed and duration information is given, implicit speed does

![Figure 4](image-url). Mean reproduced durations in Experiment 2 as a function of Speed and Stimulus Duration per Verb Form. Note: Error bars represent 95% confidence intervals of the within-subject standard error (Morey, 2008). PP stands for the personal pronoun.
not affect perceived duration like physical speed, which would imply a longer perceived duration for fast-speed than for slow-speed verbs. Nonetheless, speed information is taken into account to yield events that vary in duration with respect to speed.

Yet, does implicit speed affect perceived duration like physical speed when it is not presented in complex expressions, but linguistically isolated? Zhang et al.’s (2014) finding corroborates this assumption. They observed that the perceived duration of fast-speed verbs and adjectives (e.g. *gallop*, *rapid*) was overestimated compared to that of slow-speed verbs and adjectives (e.g. *limp*, *gradual*). Yet, this finding is in conflict with Mioni et al. (2015), who investigated the effect of implicit speed using images of vehicles associated with slow or fast speed. They report that the duration of the images of the vehicles associated with fast speed was underestimated compared to the duration of images of vehicles associated with slow speed. However, Mioni et al. (2015) only used two vehicles as stimulus material: A motorbike (representing fast speed) and a bicycle (representing slow speed), both with and without a driver. A potential issue with these items is that there are further differences apart from the associated speed, such as the physical exercise when riding a bike as opposed to driving a mechanically propelled vehicle. This difference might affect duration judgments in addition to the difference in implied speed.

Moreover, by using images instead of linguistic stimuli, they investigated the effect of speed information generated from the associated world knowledge of the pictures rather than from linguistic processing. Thus, the difference in results of Zhang et al. (2014) and Mioni et al. (2015) might simply be due to the fact, that the respective stimulus material targets different cognitive processes.

Since Zhang et al. (2014) only used ten items and did not only investigate the effect of implicit speed in manner of motion verbs but also included adjectives as stimulus material, a follow-up experiment was conducted in this study to provide further data on the effect of implicit speed on perceived duration.

### 3. Experiment 2

The motion verbs used in Experiment 1 extracted from the path PPs were employed in Experiment 2. This allowed us to examine whether linguistically encoded speed is sufficient to elicit an effect analogous to physical speed on perceived duration.

Isolating speed information was done by eliminating the path PPs and presenting the manner of motion verbs in their infinitive verb form (e.g. *to walk*; in the following referred to as verbs in infinitive form). Hence, no duration information was given to the participants since both fast and slow motion can be executed for an arbitrary amount of time. Thus, for verbs in infinitive form an effect of implicit speed on perceived duration analogous to the DEPS and the finding by Zhang et al. (2014) was expected, that is, longer perceived duration for fast-speed than for slow-speed verbs.

Furthermore, the motion verbs were inflected in third person singular in present tense with and without a personal pronoun (e.g. *she walks* and *walks*, respectively). This was done to investigate whether inflection modulates the activation of modal representations. The temporal embeddedness given in inflected but not in verbs in infinitive form might elicit the mental creation of a default path on which the motion takes place. With respect to the results of Experiment 1 of the present study, this implies that inflected manner of motion verbs might lead to an effect of implicit duration on perceived duration, since the mental creation of a default path would result in different implicit durations for fast-speed and slow-speed verbs. Analogous to Experiment 1, we expected longer perceived durations for slow-speed than for fast-speed inflected verbs.

The inflected verbs were presented with a personal pronoun (e.g. *she walks*) and without (e.g. *walks*) to disambiguate third person singular from imperative plural since these two verb forms are identical for the German manner of motion verbs used in this study. The disambiguation was implemented since the activation of modal representations can be modulated by verb form, or rather perspective (Beveridge & Pickering, 2013). While imperative elicits a first-person perspective, third person elicits an external perspective (Brunyé et al., 2009). Like Experiment 1, Experiment 2 was preregistered on the Open Science Framework (von Sobbe et al., 2019b).

### 3.1. Method

#### 3.1.1. Participants

A new sample of sixty students of the University of Tübingen took part in the second experiment and
again received either payment or course credit for their participation. Their age ranged from 17 to 60 (M = 23.63 years) and they were all native speakers of German. Due to the predefined exclusion criterion, 11 participants had to be excluded from data analysis and were replaced. All participants gave written informed consent.

### 3.1.2. Apparatus and stimuli

The apparatus was identical to Experiment 1.

The stimulus material consisted of the thirty German manner of motion verbs that had been used in Experiment 1. Three different verb form lists were constructed with these verbs, with each verb form list containing the motion verbs in a different verb form. Verb Form List 1 consisted of the verbs in infinitive verb form; Verb Form List 2 contained the verbs inflected in third person singular in present tense in combination with a personal pronoun (half of the verbs were combined with he, half of the verbs with she). The third verb form list consisted of the verbs inflected in third person singular in present tense without the use of a personal pronoun.

| List 1 | List 2 | List 3 |
|--------|--------|--------|
| bummeln| sie bummelt| bummelt |
| (to stroll)| (she strolls)| |

Seven additional motion verbs (galoppieren, traben, schippern, fahren, düsen, brettern, and tuckern) were used for the practice block. As in Experiment 1, all stimuli were presented in white colour against a grey background (Arial; scaling factor 0.07).

### 3.1.3. Procedure

One experimental session lasted about 45 min. A session consisted of one practice and three experimental blocks, which each consisted of 90 trials of the duration reproduction task. The 90 trials were defined by the factorial combination of one of the verb form lists (15 verb pairs, i.e. 30 expressions) with each expression presented in three different durations (900, 1100 or 1300 ms). The order of verb form list was counterbalanced between participants. ITI, ISI, and the recording of RDs were identical to Experiment 1. The practice block consisted of 21 trials, that is, of seven motion verbs in the three different stimulus durations. Breaks were included analogously to Experiment 1.

Participants were instructed to mentally imagine the motion denoted by the verbs of the duration reproduction task. Again, they were informed about the subsequent memory task and invited to vividly imagine the motion expressed by the verbs in order to score high in it.

In the memory task, the participants were presented with 32 motion verbs in three different verb forms. Sixteen of the presented verbs were part of the experimental stimulus material, the remaining sixteen motion verbs were verbs they had not seen before.

### 3.2. Results

Outliers were excluded following the same two-step procedure with the difference that additionally to Subject, Stimulus Duration, and Speed of Motion Verb, Verb Form List was also treated as a cell in the trimming of the data. Overall, this led to an exclusion of 1.46% of the data.

Furthermore, if the mean RDs of the remaining data of a participant did not strictly increase with the three stimulus durations, the participant’s whole data set was excluded. Consequently, the data of eleven participants had to be excluded and were replaced. Mean RDs of the two levels of Speed per Stimulus Duration and Verb Form are plotted in Figure 4.

As preregistered, RD was predicted as a function of Stimulus Duration (900 ms, 1100 ms, and 1300 ms; mean centred), Speed (fast and slow; with fast as reference category), Number of Characters (mean centred), Verb Form (infinitive, inflected with personal pronoun, and inflected without personal pronoun; infinitive was used as reference category) and an interaction of Speed and Verb Form. Item numbering was following Experiment 1, such that the pairing of Experiment 1 of fast-speed and slow-speed verbs was adopted, which resulted in 15 Items with two levels of Speed per List. Since only the verb form changed between the lists, the same Item-ID was used for all lists. Thus, each of the 15 Items consisted of two levels of Speed in three levels of Verb Form. Due to the reasons mentioned in the Results Section of Experiment 1, a sensitivity analysis was conducted, which included Block as a fixed factor (Block 1: M = 1234 (SD = 389); Block 2: M = 1314 (SD = 427); Block 3: M = 1348 (SD = 437); see Figure 5 for RDs of all cells, and Appendix D for the results of the sensitivity analysis). Including Block did not affect the results
as compared to the preregistered analysis in a meaningful way.

The random-effects structure was determined as in Experiment 1. The random-effects structure with the best AIC value had random intercepts for Subjects and Items, random slopes for the factors Speed and Stimulus Duration for Subjects, and random slopes for the factor Speed for Items. The resulting full model was $RD \sim \text{Stimulus Duration} + \text{Speed} + \text{Number of Characters} + \text{Verb Form} + \text{Speed} \times \text{Verb Form} + (\text{Speed} + \text{Stimulus Duration} | \text{Subjects}) + (\text{Speed} | \text{Items})$.

Due to the same reasons as outlined in the analysis of Experiment 1, $p$-values were obtained using the Satterthwaite’s approximation for degrees of freedom of the summary method of the lmerTest function (Kuznetsova et al., 2017) in R (Version 4.0.3, 2020).

The full model suggests an intercept of $\beta = 1273.64$ ms. The estimated coefficients of Stimulus Duration ($\beta = 564.00$, SE = 35.06, t(58.87) = 16.09, $p < .001$) and Number of Characters ($\beta = 7.71$, SE = 2.75, t(29.99) = 2.80, $p = .009$) were significant, replicating the effect of physical duration and physical size on perceived duration. There was a main effect of the Verb Form inflected with personal pronoun ($\beta = 48.60$, SE = 11.49, t(162.19) = 4.23, $p < .001$), but no main effect of the Verb Form inflected without personal pronoun ($\beta = 0.39$, SE = 8.96, t(5632.27) = 0.04, $p = .965$). Interestingly, neither the effect of Speed (with fast as reference category) for the reference Verb Form infinitive ($\beta = 13.01$, SE = 13.07, t(33.66) = 1.00, $p = .326$), nor the interaction of Speed and the Verb Form inflected with personal pronoun was significant ($\beta = -12.31$, SE = 12.32, t(15660.86) = -1.00, $p = .318$). However, the interaction of Speed and the Verb Form inflected without a personal pronoun was significant ($\beta = 24.55$, SE = 12.33, t(15460.24) = 1.99, $p = .046$). Thus, the factor Speed only modulated the Verb Form inflected without a personal pronoun.

Speed was not significant for the reference Verb Form infinitive. Numerically, however, RDs of slow-speed verbs were not lower – as predicted – but higher than RDs of fast-speed verbs. To rule out the possibility that the result in Experiment 2 is a false negative result with an actual effect that is comparable to the one observed in Experiment 1, a simulation-based post hoc power analysis was performed using the R package simr (Green & MacLeod, 2016). Of 1000 datasets simulated from the full model but with a Speed effect of 94.74 ms adopted from Experiment 1, 100% resulted in a significant Speed effect according to $p$-values using the Satterthwaite’s approximation for degrees of freedom. Thus, the power should be sufficient to detect an effect of

Figure 5. Mean reproduced durations in Experiment 2 as a function of Speed and Stimulus Duration per Block and Verb Form.

Note: Error bars represent 95% confidence intervals of the within-subject standard error (Morey, 2008). PP stands for the personal pronoun.
Speed for isolated verbs in infinitive form, if it was as high as the one for manner of motion verbs in complex expressions (in Experiment 1).

However, the effect of implicit stimulus attributes on perceived duration could be smaller for single words than for complex verb phrases (such as in Experiment 1), but still meaningful. Therefore, the effect of Speed for the Verb Form inflected without a personal pronoun could serve as a better source for the effect size one would like to detect with a certain power. To obtain the estimated coefficient for Speed in Verb Form List 3, that is, for inflected verbs without personal pronoun, the LMEM was re-estimated with Verb Form List 3 as reference category. The full model including all coefficients is reported in Appendix E. The effect of Speed was significant for the reference Verb Form inflected without a personal pronoun ($\beta = 37.56$, $SE = 13.30$, $t(34.06) = 2.82$, $p = .008$). This estimate was applied in 1000 simulations from the original model, again using the simr package. Of these, 77.50% resulted in a significant Speed effect according to $p$-values using the Satterthwaite’s approximation for degrees of freedom. Thus, the power for detecting a Speed effect as high as the one for isolated inflected verbs (in Verb Form List 3) for isolated verbs in infinitive form (in Verb Form List 1) was concluded to be acceptable.

Mean CV was calculated for each Participant, Stimulus Duration, Verb Form, and both levels of Speed by dividing the standard deviation by the mean of the respective cell. Mean CV for a Stimulus Duration of 900 ms was 0.23, mean CV for a Stimulus Duration of 1100 ms was 0.21, and for 1300 ms it was 0.20.

Participants performed well in the memory task. The mean hit rate was 91.88%. The false alarm rate for new items was 5.63%.

### 3.3. Discussion

Even though motion verbs in infinitive form presented without context have a high salience of speed information, RDs did not reflect the pattern that was reported for physical speed, that is, longer RDs for fast than for slow motion (Brown, 1995; Kanai et al., 2006; Kaneko & Murakami, 2009; Karşılar et al., 2018; Linares & Gorea, 2015; Tomassini et al., 2011). We had expected to replicate the findings by Zhang et al. (2014), who observed an effect of implicit speed on perceived duration analogous to physical speed in a temporal bisection task (i.e. a DEIS). However, in the present experiment, the estimated coefficient for the factor Speed was not significant for the manner of motion verbs in infinitive form. Numerically, however, slow-speed verbs were reproduced longer, not shorter than fast-speed verbs, which does not correspond to the predicted pattern, but is reminiscent of the effect observed in Experiment 1.

To assess whether the effect of Speed on the perceived duration for verbs in infinitive form in fact behaved as observed by Mioni et al. (2015), that is, longer RDs for slow-speed than for fast-speed verbs, we conducted two post-hoc simulation-based power analyses, one in which the effect of the factor Speed was assumed to be equivalent to the one observed in Experiment 1 and one in which it was assumed to be equivalent to the one observed for single manner of motion verbs inflected without personal pronoun. The second power analysis was conducted, since richer stimuli such as complex expressions might elicit deeper semantic processing compared to isolated words (Bedny & Caramazza, 2011; Miller et al., 2018), such that the effect of Speed for the Verb Form inflected without a personal pronoun might be a better estimate for the actual effect size. Yet, both power analyses indicated that the power was high enough to consider a false negative result as unlikely.

Inflected verb forms of the manner of motion verbs were instead predicted to have an effect on perceived duration analogous to Experiment 1. This was based on the assumption that the temporal saturation due to the inflection of the verbs might elicit the mental creation of a default path on which the motion takes place. As a consequence, inflected motion verbs would provide duration information, with longer events for slow-speed verbs than for fast-speed verbs. Thus, the factor Speed was expected to affect RDs analogously to Experiment 1: Just like physical duration, implicit duration should increase RDs. While RDs of inflected motion verbs presented without personal pronoun behaved in the predicted way, this was not the case for RDs of inflected motion verbs presented with a personal pronoun. Accordingly, temporal saturation cannot be considered the cause of the effect on RDs for the inflected motion verbs presented without a personal pronoun. The contribution of verb form for the establishment of a representation of the temporal structure of a linguistically expressed event remains to be investigated by future studies.
Personal pronouns were included to disambiguate third person singular from imperative plural, since these two inflections are identical for the German manner of motion verbs used as stimuli in this study. There was a significant main effect of the Verb Form *inflected with personal pronoun* most likely stemming from the fact that the personal pronouns systematically increased the length of all items compared to the other two Verb Forms. Moreover, inflected verbs with personal pronoun can be considered sentential units consisting of a pronominal subject and a predicate, while inflected verbs without personal pronouns and verbs in infinitive form are lexical units. This difference in complexity might be another reason for the significant main effect of the Verb Form *inflected with personal pronoun*.

Overall, the results suggest, that the dilation effect of speed only holds for physical, but not for implicit speed and is thus in conflict with the study by Zhang et al. (2014). With respect to the inflected manner of motion verbs without personal pronoun, the results of Experiment 2 corroborate the findings of Mioni et al. (2015), who observed an overestimation of the presentation duration of pictures associated with slow speed compared to pictures associated with fast speed.

4. Experiment 3

The results of Experiment 2 are in conflict with the results of Zhang et al. (2014). However, there are two differences between Experiment 2 and their study. Firstly, the stimulus material they used was slightly different since they did employ a smaller amount of stimuli and a wider range, that is, they used manner of motion verbs and adjectives conveying the two levels of speed, fast and slow. Secondly, they implemented a temporal bisection task, while participants in our experiment were asked to reproduce the duration of the presented expressions. To assess whether the difference in results can be attributed to the temporal tasks chosen, we replicated the temporal bisection task used by Zhang et al. (2014). In their study, participants were instructed to learn a short (i.e. 400 ms) and a long (i.e. 1200 ms) standard duration and were subsequently asked to indicate whether the presentation duration of fast-speed and slow-speed verbs and adjectives was closer to the short or the long standard duration. We included a larger amount of fast-speed and slow-speed verbs, but did not include adjectives to generate a more homogenous but larger group of items. We followed their experimental design as closely as possible. The experiment was preregistered on the Open Science Framework (von Sobbe et al., 2021).

In temporal bisection studies, the proportions of “long” responses are taken as a measure of the perceived duration. Moreover, the temporal bisection point (TBP), just noticeable difference (JND) and Weber fraction can be estimated with help of logistic psychometric functions that are fitted for the proportions of “long” responses. TBP, also referred to as the point of indifference (Maricq et al., 1981), indicates the duration at which participants are equally likely to give a “short” or a “long” response (Kopec & Brody, 2010). The TBP is the 50% point of the logistic psychometric function (Zhang et al., 2014). A lower TBP implies an overestimation of duration, since the participants judge the comparison durations as being “long” earlier compared to a higher TBP. JND and Weber fraction are measures of the participants’ temporal discriminability. JND refers to the smallest duration that leads to a change in a participant’s behaviour (Kopec & Brody, 2010). It is calculated as the half difference between the durations at which 25% and 75% “long” responses are given, which are retrieved from the logistic psychometric function (Zhang et al., 2014). JND and Weber fraction, that is, JND divided by TBP, indicate the steepness of the psychometric function. A steeper psychometric function indicates good discriminability and results in a lower Weber fraction, while a higher Weber fraction indicates a more gradual psychometric function and a poorer discriminability (Kopec & Brody, 2010).

In the study by Zhang et al. (2014), participants overestimated the presentation duration of fast-speed verbs and adjectives compared to that of slow-speed verbs and adjectives. Firstly, this was detectable in a higher proportion of “long” responses for fast-speed compared to slow-speed verbs and adjectives at a duration of 800 ms (but not at durations of 400, 600, 1000, and 1200 ms). Secondly, this overestimation of fast-speed verbs and adjectives was apparent in a lower TBP for fast-speed verbs and adjectives compared to the TBP of slow-speed verbs and adjectives. JND and Weber fraction were not affected by the level of Speed.

4.1. Method

4.1.1. Participants

We raised the number of participants from 32 in the study by Zhang et al. (2014) to 500 in the replication
to increase statistical power. Due to a pre-defined exclusion criterion (see Procedure for details), we had to discard the data of 46 participants. Seven more participants were excluded since these participants’ response pattern revealed that they did not follow or understand the task instructions properly.¹ These fifty three participants’ data was replaced to reach the pre-determined sample size. Participants were native speakers of German (207 female, 289 male, and 4 with diverse gender) and recruited using Prolific (www.prolific.co). They received reimbursement based on an hourly wage of 9 Euro (specifically, they were payed £1.10 for an experimental session of 8 min). The mean age was 28.73 years (SD = 8.68). 443 reported being right-handed, 46 were left-handed, and the remaining 11 reported being ambidextrous. They were naïve with respect to the purpose of investigation. All participants gave informed consent.

4.1.2. Apparatus and stimuli

The experiment was programmed in PsychoPy v2020.1.3 and was run online via Pavlovia.org. The standard visual stimuli for the training session were white filled squares presented against a black background in the centre of the screen (scaling factor 0.1). Comparison stimuli were 11 slow-speed and 11 fast-speed verbs in infinitive form (see Table 2) that were selected from the rating study conducted for Experiment 1 (see Appendix A for details). The verbs in the two levels of Speed did not differ in number of characters or number of syllables. Moreover, the frequency was not significantly different for the two levels of Speed (t(14.66) = 0.68, p = .508). The words were presented in the centre of the computer screen in white against a black background (Arial; scaling factor 0.04). The keys “d” and “k” were used as response buttons.

4.1.3. Procedure

Just like Zhang et al. (2014) we had the two factors Speed (fast vs. slow) and Comparison Duration (400, 600, 800, 1000, and 1200 ms) in a within-subjects design. In the study by Zhang et al. (2014) all stimulus words consisted of two Chinese characters. In our stimulus material, the number of characters was identical for the two levels of Speed. Yet, there was equal variation in the number of characters within each level of Speed. More specifically, both levels of Speed consisted of the same amount of verbs with five to eight characters (see Table 2 for details). However, in a temporal bisection study by Karšılars and Balci (2019), no effect of physical stimulus size on perceived duration was observed when the stimuli contained or implied symbolic meaning. Since this also applies to the stimuli of the present experiment, no modulation of perceived duration by the number of characters was expected.

One experimental session consisted of a training session and a test session. Prior to the training session, participants were told to keep in mind a short (400 ms) and a long (1200 ms) presentation duration of a white square, i.e. the visual standard stimulus. Both durations were presented to them once for the purpose of acquaintance. In the training session, participants were asked to discriminate these two durations and to give their response with one of the two response buttons, “d” (i.e. “short duration”) and “k” (i.e. “long duration”) with the index finger of the left and right hand, respectively. The training session consisted of the white square presented for the short (400 ms) or the long (1200 ms) duration, with each duration being repeated five times in randomised order. Subsequent to the presentation of the square, a red exclamation mark (“!”) appeared on the screen, which prompted the participants to give a response. The ITI was 1 s. If participants failed to reach an accuracy of at least 80% in the training session, this was taken as an indication that they did not understand the instruction. Their data was thus excluded from the analysis.²

Before the test session, the participants were told that they were now going to see words instead of a square and that their task was to indicate via keypress (“d” and “k”) whether the presentation duration of the word was closer to the short or the long standard duration. They initiated the test session with the space bar. Like in the training session, a red exclamation mark appeared

¹More specifically, three of these participants did not distinguish between the two levels of standard duration but between the two levels of Speed. The other four participants answered randomly without any clear pattern such that they were presumably simply clicking through the experiment. These participants were spotted since the TBPs of their fitted logistic functions were outside the range of the comparison durations. Since this additional exclusion of participants was not part of the pre-registered exclusion procedure, we conducted a sensitivity analysis including these participants, which did not change the results in a meaningful way (see Appendix F).

²Note that accuracy in the training session of all participants in Zhang et al. (2014) was 100%.
Table 2. Manner of motion verbs for Experiment 3.

| Verb (to walk) | Slow-speed verbs | Fast-speed verbs |
|----------------|------------------|------------------|
| gehen          | Rating 3.34      | Rating 6.55      |
| (to limp)      | Letters 5        | Letters 5        |
| (to stagger, to wobble) | Syllables 2     | Syllables 2       |
| ranken         | Frequency 6       | Frequency 14      |
| (to plod)      |                  |                  |
| humpeln        |                  |                  |
| (to hobble)    |                  |                  |
| tapen          |                  |                  |
| (to stagger)   |                  |                  |
| (to stagger, to totter) |             |                  |
| bummeln        |                  |                  |
| (to stroll)    |                  |                  |
| (to trudge)    |                  |                  |
| latschen       |                  |                  |
| (to triapse)   |                  |                  |
| stiefeln       |                  |                  |
| (to stride forcefully) |           |                  |
| SD             |                  |                  |
| M              |                  |                  |

Note: Rating refers to the mean rated speed on a 7 point Likert scale (1 representing very slow, 7 representing very fast). Letters stand for the number of characters of the verbs in the infinitive verb form. Frequency refers to the verbs’ frequency class obtained from Leipzig Corpora Collection (2018).

subsequent to the stimulus as a prompt to respond. ITI was identical to the training session. Participants were asked to focus the centre of the screen throughout the experiment. One test session consisted of 110 trials (i.e. 22 verbs × 5 comparison durations) that were presented in randomised order.

4.2. Results

Mean accuracy in the training session was 92.21% (SD = 17.02).

Analogous to Zhang et al. (2014), the proportions of “long” responses were calculated for each level of Speed and each Subject (see Figure 6). TBP, JND, and Weber fraction were calculated as outlined in Zhang et al. (2014), that is, based on logistic psychometric functions fitted for “long” responses for each level of Speed against the comparison durations for each participant using the quickpsy function in R (Linares & López-Moliner, 2016). Repeated-measures ANOVAs were calculated on the proportions of “long” responses, TBP, JND, and Weber fraction using the ezANOVA function in R (Arnhold, 2014).

On the proportions of “long” responses, a 2 (Speed) × 5 (Comparison Duration) repeated-measures ANOVA was performed. Like in the study by Zhang et al. (2014) the main effect of Comparison Duration was significant [F(4, 1996) = 6033.77, p < .001, ηp2 = .92, p-value was Greenhouse-Geisser adjusted]. However, unlike in the study by Zhang et al. (2014), neither the main effect of Speed [F(1, 499) = 0.06, p = .801, ηp2 < .01], nor the interaction of Speed and Comparison Duration [F(4, 1996) = 2.04, p = .104, ηp2 < .01, p-value was Greenhouse-Geisser adjusted] was significant.

Different to Zhang et al. (2014), who reported a significant effect of Speed on TBPs, the three one-way ANOVAs calculated on TBP, JND, and Weber fraction in the present study indicated that none of these measures was influenced by Speed. More specifically, the mean TBP for fast-speed verbs was 771 ms (SD = 101), while the mean TBP for slow-speed verbs was 772 ms (SD = 102) [F(1, 499) = 0.16, p = .690, ηp2 < .01]. Mean JND for fast-speed verbs was 110 ms (SD = 69); mean JND for slow-speed verbs was 111 ms (SD = 68) [F(1, 499) = 0.34, p = .558, ηp2 < .01]. Weber fraction for fast-speed verbs was M = 0.14 (SD = 0.10); Weber fraction for slow-speed verbs was M = 0.14 (SD = 0.09) [F(1, 499) = 0.02, p = .899, ηp2 < .01].

4.3. Discussion

Unlike Zhang et al. (2014), neither the proportions of “long” responses nor the TBP were modulated by the level of speed associated with the manner of
motion verbs. Despite the increased power in the current experiment (500 participants compared to 32 in the study by Zhang et al., 2014), we could not replicate the original findings. Moreover, mean TBP and Weber fraction in the present experiment broadly adhere with previous temporal bisection studies (Kopec & Brody, 2010; Wearden & Lejeune, 2008). Thus, participants seem to have performed the task as required.

The results of Experiment 3 are in line with the results of Experiment 2 despite the use of a different temporal task. The associated level of speed of verbs in infinitive form does not affect perceived duration like physical speed, for which an overestimation of fast compared to slow motion was observed (Brown, 1995; Kanai et al., 2006; Kaneko & Murakami, 2009; Karşilar et al., 2018; Linares & Gorea, 2015; Tomassini et al., 2011). Thus, we assume that the finding by Zhang et al. (2014) might either reflect a false positive finding, or the effect they observed was driven by specific items of their stimulus material and thus would not generalise to the present stimulus material.

5. General discussion

By implementing both duration reproduction tasks (Experiments 1 and 2) and a temporal bisection task (Experiment 3), the present study investigated whether mental images elicited by complex linguistic stimuli affect perceived duration and, if so, how different aspects of the expressions contribute while doing so. More precisely, in Experiment 1 we presented expressions that denoted short and long events yielded by two levels of speed associated with manner of motion verbs while keeping the path constant. Therefore, the expressions contained information about two competing attributes that both affect perceived duration when they are physically present: duration and speed (Matthews & Meck, 2016). Previous studies have shown that an increase in physical duration and faster physical speed both lead to an increase in RDs (Brown, 1995). In the expressions employed in Experiment 1, fast-speed verbs implied a shorter event than slow-speed verbs, since covering a certain path with a slow movement takes longer than covering the same path with a fast movement. Thus, depending on which source of information was more salient for the generation of the mental image, different patterns of RDs were expected.

Indeed, RDs were modulated by the linguistic expressions in Experiment 1, such that expressions with fast-speed verbs had shorter reproduction times than expressions with slow-speed verbs. This pattern of results corresponds to an effect that is attributable to implicit duration information, but not to implicit speed information, for which – analogous to physical speed – longer RDs for expressions with fast-speed than slow-speed verbs were
predicted (see Wang & Gennari, 2019, for converging results on language-mediated temporal memory distortions).

In Experiment 2, we presented only the manner of motion verbs of Experiment 1 to control whether implicit speed in fact has an analogous effect to physical speed when it is not competing with duration information. However, the speed information given in isolated manner of motion verbs in infinitive form did not modulate RDs. Since this finding is in conflict with the study by Zhang et al. (2014), we replicated their temporal bisection task in Experiment 3 to assess whether the difference in results was due to the temporal tasks chosen. Yet, the replication of the study by Zhang et al. (2014) was unsuccessful. The associated speed of verbs in infinitive form did not modulate perceived duration, irrespective of the task that was implemented.

Beyond the assessment of an effect of implicit speed on perceived duration, this finding is valuable for methodological reasons. Even though temporal bisection and temporal reproduction tasks have been employed in distinct studies that investigate the same non-temporal stimulus attribute effect (see Cai & Wang, 2014 for a temporal reproduction task; see Oliveri et al., 2008 for a temporal bisection task to investigate the effect of numerical magnitude on perceived duration), there is a lack of a direct comparison in the literature between the two tasks when assessing the effects of non-temporal stimulus attributes on perceived duration. The results of Experiment 2 and 3 suggest that both tasks can be used interchangeably without producing different results.

Mioni et al. (2015), who also implemented a temporal bisection task when investigating the effect of images of vehicles associated with either fast or slow speed on perceived duration, observed an opposite pattern to Zhang et al.’s (2014) study, that is, an underestimation of fast compared to slow speed. This is in line with the pattern of RDs for manner of motion verbs inflected in third person singular without personal pronoun in Experiment 2 of this study. Interestingly, we observed a null-effect for manner of motion verbs inflected in third person singular with personal pronoun, analogous to the verbs in infinitive form in Experiment 2. One might hypothesise that the inflected verbs without personal pronouns were confused with imperative plural by the participants due to their identical phenotype. Since imperative has a high action relevance and directly addresses the reader, this might be the reason why the mental image was strong enough to yield an effect of implicit speed on RDs. Future studies will have to investigate whether there is a systematic difference in the depth of mental images elicited by third person versus imperative verb phrases.

However, it remains unanswered, why implicit speed does not modulate RDs like physical speed, for which an overestimation of fast compared to slow speed has been reported (Brown, 1995; Kanai et al., 2006; Kaneko & Murakami, 2009; Karşılıar et al., 2018; Linares & Gorea, 2015; Tomassini et al., 2011). In case of the complex expressions in Experiment 1, the participants are faced with linguistically expressed events. According to Zacks and Tversky, events are “a segment of time at a given location that is perceived by an observer to have a beginning and an end” (Zacks & Tversky, 2001) and are recognised on the basis of their temporal structure. Thus, temporal information is essential for the perceiving, thinking, and talking about events (Zwaan & Radvansky, 1998). This offers a straightforward explanation why RDs in Experiment 1 were modulated according to duration, but not speed information: The expressions are processed as a particular instance of a motion event and are encoded in working memory indexed according to their temporal information (Zwaan & Radvansky, 1998).

With respect to the manner of motion verbs in infinitive form in Experiments 2 and 3, on the contrary, linguistically speaking participants are faced with atelic processes but not events. However, the mental imagination of atelic motion without a particular bounding in space and time is challenging, if not impossible. This might be the reason why an effect of linguistically expressed speed analogous to physical speed on perceived duration could not be traced. It might simply be too difficult to imagine the denoted motion without the mental generation of a default path on which the motion takes place, which then again produces duration information. This would also explain the pattern of RDs observed for inflected manner of motion verbs without personal pronoun in Experiment 2, that is, longer RDs for slow-speed than for fast-speed verbs, a pattern that is in accordance with inferred duration.

Is it possible that the results of the present study are influenced by the understanding of the experimental aims by the participants? Indeed, some
participants identified the object of investigation as indicated by a follow-up survey subsequent to the experimental sessions in Experiments 1 and 2, while other participants assumed our cover story to be true, which was designed to foster the engagement with imagery processes (see Procedure Section of Experiment 1 for details). Yet, even though some participants in both experiments assumed that we were investigating an effect of associated speed on perceived duration, the outcome of the two experiments are not identical. Thus, we consider it unlikely that the results are only explicable by means of a conscious manipulation by the participants. However, we acknowledge that this is a potential draw-back of our paradigm, which could be addressed better in future studies, for example, by including filler items to mask the purpose of the study altogether.

Against the background of grounded cognition, our findings provide mixed results. The mental representation of speed expressed via single manner of motion verbs in infinitive form is not as analogous to the mental representation of physical speed as suggested by strong versions of embodied cognition, since it does not affect perceived duration as physical speed does. Linguistically expressed duration, on the other hand, affects RDs analogous to actual duration. The results of Experiment 1 on more complex phrases in conjunction with the results of Experiments 2 and 3 on single words corroborate the assumption that richer linguistic stimuli elicit deeper semantic processing and are thus more likely to produce activation of the associated modal representations (Bedny & Caramazza, 2011; Miller et al., 2018), since only complex expressions, but not verbs in infinitive form had an effect on perceived duration. Moreover, even though the kinematic information is specifically salient in the expressions of Experiment 1, the modal representations are not reduced to the corresponding motoric simulation, but also contain the compositional integration of the path. Thus, the underlying simulations reproduce the described events in their temporal structure, that is, longer events for slow motion than for fast motion when the path is kept constant, which yields nuanced representations of the events’ durations denoted by the linguistic expressions.

In summary, our results suggest that complex linguistic expressions have the potential to act on the internal clock analogous to the physical counterparts that are denoted by these expressions. More specifically, the duration of the events denoted by the present study’s expressions affect RDs analogous to physical duration, that is, longer RDs for longer events compared to shorter events. Even though the modulation of duration depends on the underlying speed information, linguistically expressed speed does not affect RDs like physical speed. This might be related to the difficulty of imagining speed without being bound in time and space and detaching speed from duration information.

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Data availability statement

The data that support the findings of this study are openly available in TALAR – Tübingen Archive of Language Resources at https://talar.sfb833.uni-tuebingen.de/, with persistent identifier https://hdl.handle.net/11022/0000-0007-EBF2-F.

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References

Allman, M., Teki, S., Griffiths, T. D., & Meck, W. H. (2014). Properties of the internal clock: First- and second-order principles of subjective time. Annual Reviews
von Sobbe, L., Reiber, F., Ulrich, R., Maienborn, C., & Scheifele, E. (2021). BVR_3 (Replication of Zhang et al. 2014). osf.io/ntqp9.

von Sobbe, L., Ulrich, R., Maienborn, C., & Scheifele, E. (2019a). BVR_1. Retrieved from osf.io/s9hgf.

von Sobbe, L., Ulrich, R., Maienborn, C., & Scheifele, E. (2019b). BVR_2. Retrieved from osf.io/nwat8.

Wang, Y., & Gennari, S. P. (2019). How language and event recall can shape memory for time. Cognitive Psychology, 108, 1–21. https://doi.org/10.1016/j.cogpsych.2018.10.003

Wearden, J. H., & Lejeune, H. (2008). Scalar properties in human timing: Conformity and violations. Quarterly Journal of Experimental Psychology, 61(4), 569–587. https://doi.org/10.1080/17470210701282576

Wittmann, M. (2009). The inner experience of time. Philosophical Transactions of the Royal Society B: Biological Sciences, 364, 1955–1967. https://doi.org/10.1098/rspb.2009.0003

Yamamoto, K., & Miura, K. (2012). Time dilation caused by static images with implied motion. Experimental Brain Research, 223, 311–319. https://doi.org/10.1007/s00221-012-3259-5

Zacks, J. M., & Tversky, B. (2001). Event structure in perception and conception. Psychological Bulletin, 127(1), 3–21. https://doi.org/10.1037/0033-2909.127.1.3

Zhang, Z., Jia, L., & Ren, W. (2014). Time changes with feeling of speed: An embodied perspective. Frontiers in Neurorobotics, 8, 14. https://doi.org/10.3389/fnbot.2014.00014

Zwaan, R. A., & Radvansky, G. A. (1998). Situation models in language comprehension and memory. Psychological Bulletin, 123(2), 162–185. https://doi.org/10.1037/0033-2909.123.2.162

Appendices

Appendix A

Motion verbs of the pre-study were extracted from Schröder (1993) based on the pre-condition that they denoted human motion. This resulted in the incorporation of 71 motion verbs out of the 191 motion verbs that are listed in Schröder. Additionally, five control verbs denoting no motion (four verbs) or being a non-word (one verb) were included in the pre-study. Since some of Schröder’s verbs are antiquated, participants were asked to either rate the speed of the motion verbs on a 7-point scale from 1 (very slow) to 7 (very fast), or choose one of the three alternative options Word does not denote locomotion, I am not acquainted with the word, or Speed is not univocal. The pre-study was programmed using PsychoPy v1.90.3. Pre-selection criteria for motion verbs as stimulus material was that at least 80% of the participants had selected to rate the speed (applied to 39 of the 71 motion verbs) and that standard error of the speed rating was below 0.2 (applied to 49 of the 71 motion verbs and led to the exclusion of 2 of the 39 previously mentioned motion verbs). Additionally, a balance of fast and slow motion, frequency class, number of characters,
and number of syllables was considered in the selection of the final stimulus material, which consisted of 28 motion verbs. The mean percentage of participants who chose to rate the speed and did not make use of the alternative options for these 28 motion verbs was 93.13% (SD = 4.35%) and the mean standard error of the speed rating was 0.13 (SD = 0.02). Two further verbs, schlurfen and joggen that are not listed by Schröder, were included in the stimulus material. The two verbs’ speed had been rated by 40 participants in a different pre-study of another, independent experiment. Participants in that pre-study were only asked to rate the speed on a 7-point scale. They did not have alternative options to choose from. To ensure that the rating was comparable in both pre-studies, a Pearson correlation was calculated on the means of the 26 motion verbs that were tested in both pre-studies (r =.99), showing a high correspondence. To classify the verbs as either slow or fast, a value of 3.5 in the speed rating was taken as boundary value.

The resulting group of slow-speed verbs had a mean rating of 2.36 (SD = 0.59), while the group of fast-speed verbs had a mean rating of 5.68 (SD = 0.68). This difference of means was significant (t(14) = 31.60, p < .001). Importantly, neither the difference of number of characters, number of syllables, nor frequency was significantly different in the two speed of motion verb conditions (number of characters: t(27.54) = 1.51, p = .143; number of syllables: t(28) = 0.00, p > .999; frequency: t(21.06) = 0.61, p = .551).

Appendix B

To evaluate whether including Block as predictor had an impact on the results of the fixed factors included in the preregistered analysis of Experiment 1, we predicted RD as a function of Stimulus Duration (1050 ms and 1300 ms; mean centred), Speed (fast and slow; with fast as reference category), Number of Characters (encoded numerically and mean centred), and Block (three levels, effect coded). The random effects structure was determined analogous to the random effects structure of the main analysis. The one with the best AIC value included random intercepts for Subjects and Items, and random slopes for the factor Speed for Subjects. All reduced models converged such that model comparison using -values were again obtained using the Satterthwaite’s approximation for degrees of freedom of the summary method of the lmerTest function (Kuznetsova et al., 2017) in R (Version 4.0.3, 2020). The full model suggests an intercept of $\beta = 1597.94$ ms. As in the main analysis, the estimated coefficients of Stimulus Duration ($\beta = 584.22, SE = 37.05$, t (10095.93) = 15.77, p < .001), Number of Characters ($\beta = 7.19, SE = 1.57, t(61.52) = 4.57, p < .001$), and Speed ($\beta = 764.47, SE = 9.44, t(9804.17) = 8.10, p < .001$) were significant. However, the estimated coefficient of Frequency was not significant ($\beta = -0.76, SE = 2.03, t(481.84) = -0.37, p = .709$).

Appendix C

As outlined in the preregistration, we conducted an exploratory analysis to assess the potential effect of the verbs’ frequencies on RDs. Firstly, a repeated measures correlation was calculated using the rmcorr package in R (Bakdash & Marusich, 2017). The mean correlation coefficient across participants was not significant (r(10141) = .00, 95% CI [−0.02, 0.02], p = .899). Secondly and in addition to the preregistered exploratory analysis, we included Frequency as fixed factor in the LMEM. Thus, we predicted RD as a function of Stimulus Duration (1050 ms and 1300 ms; mean centred), Speed (fast and slow; with fast as reference category), Number of Characters (encoded numerically and mean centred), and Frequency (encoded numerically and mean centred). The random effects structure was determined analogous to the random effects structure of the main analysis. There was only one model that converged and that did not over-fit the data. It included random intercepts for Subjects and Items. To provide comparability, -values were again obtained using the Satterthwaite’s approximation for degrees of freedom of the summary method of the lmerTest function (Kuznetsova et al., 2017) in R (Version 4.0.3, 2020). The full model suggests an intercept of $\beta = 1597.94$ ms. As in the main analysis, the estimated coefficients of Stimulus Duration ($\beta = 584.22, SE = 37.05$, t (10095.93) = 15.77, p < .001), Number of Characters ($\beta = 7.19, SE = 1.57, t(61.52) = 4.57, p < .001$), and Speed ($\beta = 764.47, SE = 9.44, t(9804.17) = 8.10, p < .001$) were significant.

Appendix D

Analogous to Appendix B and Experiment 1, Block was included as predictor in the preregistered analysis of Experiment 2. Consequently, RD was predicted as a function of Stimulus Duration (900 ms, 1100 ms, and 1300 ms; mean centred), Speed (fast and slow; with fast as reference category), Number of Characters (mean centred), Verb Form (infinitive, inflected with personal pronoun, and inflected without personal pronoun; infinitive was used as reference category), an interaction of Speed and Verb Form, and Block (three levels, effect encoded). The random effects structure was determined analogously to the previous analyses. The one with the best AIC value included random intercepts for Subjects and Items, and random slopes for the factor Speed for Subjects and for Items, as well as random slopes for the factor Stimulus Duration for Subjects. Since the full model did not converge when estimated with maximum likelihood instead of restricted maximum likelihood, model comparison using $\chi^2$ difference tests could not be conducted. Thus, -values were again obtained using the Satterthwaite’s
approximation for degrees of freedom of the summary method of the \textit{lmertest} function (Kuznetsova et al., 2017) in R (Version 4.0.3, 2020). The full model suggests an intercept of $\beta = 1273.57$ ms. As in the main analysis, the estimated coefficients of Stimulus Duration ($\beta = 563.89, SE = 35.12, t(58.86) = 16.06, p < .001$), Number of Characters ($\beta = 7.62, SE = 2.74, t(30.09) = 2.78, p = .009$), the Verb Form \textit{inflected with personal pronoun} ($\beta = 48.90, SE = 11.40, t(159.25) = 4.29, p < .001$), and the interaction of Speed with the Verb Form \textit{inflected without a personal pronoun} ($\beta = 24.39, SE = 12.18, t(15444.47) = 2.00, p = .045$) were significant. Neither Speed in the reference Verb Form \textit{indefinitive} ($\beta = 13.23, SE = 13.05, t(33.25) = 1.01, p = .318$), nor the Verb Form \textit{inflected without personal pronoun} ($\beta = 0.45, SE = 8.86, t(5511.31) = 0.05, p = .959$), nor the interaction of Speed and the Verb Form \textit{inflected with personal pronoun} ($\beta = -12.33, SE = 12.18, t(15652.94) = -1.01, p = .311$) were significant. However, the estimated coefficients of Block 1 ($\beta = -65.62, SE = 3.50, t(15750.31) = -18.74, p < .001$) and Block 2 ($\beta = 16.21, SE = 3.51, t(15750.27) = 4.62, p < .001$) were both significant. This yields an estimated mean of 1207.95 ms for Block 1, of 1289.78 ms for Block 2, and of 1322.98 ms for Block 3.

**Appendix E**

The re-estimated LMEM with Verb Form List 3 (i.e. \textit{inflected without personal pronoun}) as reference category contained the same fixed effects as the preregistered analysis of Experiment 2. RD was predicted as a function of Stimulus Duration (900 ms, 1100 ms, and 1300 ms; mean centred), Speed (\textit{fast} and \textit{slow}; with \textit{fast} as reference category), Number of Characters (mean centred), Verb Form (\textit{indefinitive}, \textit{inflected with personal pronoun}, and \textit{inflected without personal pronoun}; \textit{inflected without personal pronoun} was used as reference category), and an interaction of Speed and Verb Form. The random effects structure was determined analogously to the previous analyses. The one with the best AIC value included random intercepts for Subjects and Items, and random slopes for the factor Speed for Subjects and for Items, as well as random slopes for the factor Stimulus Duration for Subjects. Due to the same reason as outlined in the analysis of Experiment 1, $p$-values were again obtained using the Satterthwaite’s approximation for degrees of freedom of the summary method of the \textit{lmertest} function (Kuznetsova et al., 2017) in R (Version 4.0.3, 2020). The full model suggests an intercept of $\beta = 1274.04$ ms. The estimated coefficients of Stimulus Duration ($\beta = 564.00, SE = 35.06, t(58.86) = 16.09, p < .001$), Number of Characters ($\beta = 7.71, SE = 2.75, t(29.99) = 2.80, p = .009$), and the Verb Form \textit{inflected with personal pronoun} ($\beta = 48.21, SE = 13.05, t(97.07) = 3.70, p < .001$) were significant. Importantly, the effect of Speed in the reference Verb Form \textit{inflected without a personal pronoun} was also significant ($\beta = 37.56, SE = 13.30, t(34.06) = 2.82, p = .008$). Moreover, the effect of Speed in the other two Verb Form Lists were significantly different from the effect of Speed in the reference Verb Form (\textit{speed} \times \textit{Verb Form indefinitive}: $\beta = -24.55, SE = 12.33, t(15460.27) = -1.99, p = .046$; \textit{speed} \times \textit{Verb Form inflected with personal pronoun}: $\beta = -36.86, SE = 12.29, t(15760.04) = -3.00, p = .003$). The Verb Form \textit{indefinitive} was not significant ($\beta = -0.39, SE = 8.96, t(5632.55) = -0.04, p = .965$).

**Appendix F**

To ensure that the results of the main analyses were not sensitive with respect to the exclusion of the seven participants, whose estimated TBP scores were outside the range of the comparison durations (i.e. below 400 ms or above 1200 ms), we conducted the analyses as outlined in the Results Section of Experiment 3, but included the respective seven participants. Like in the main analysis there was only a main effect of Comparison Duration on the proportions of “long” responses [$F(4, 204) = 5299.57, p < .001$, $\eta^2_p = .91$, $p$-value was Greenhouse-Geisser adjusted], but no main effect of Speed [$F(1, 506) = 0.36, p = .549$, $\eta^2_p < .01$], and no interaction of Speed and Comparison Duration: [$F(4, 204) = 2.19, p = .084$, $\eta^2_p < .01$, $p$-value was Greenhouse-Geisser adjusted].

Analogously, there was no significant main effect of Speed in the three one-way ANOVAs on TBP [$F(1, 506) = 0.63, p = .429$, $\eta^2_p < .01$], JND [$F(1, 506) = 1.62, p = .204$, $\eta^2_p < .01$], and Weber fraction [$F(1, 506) = 0.10, p = .746$, $\eta^2_p < .01$].