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Filters for optimal smoothing of acoustic and electric blink reflex EMG responses to determine blink response magnitude

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ABSTRACT

The functional (i.e., kinematic) aspects of the blink reflex depend on the size of the integrated orbicularis oculi EMG response. Peak amplitude of smoothed rectified EMG is often used as an approximation of integrated EMG. A comparison was made between the outputs of 24 different smoothing filters, correlating peak amplitude of acoustic or electric blink reflexes with integrated EMG. The coefficient of determination (R^2) was largest (i.e., ≥.95 for acoustic and ≥.90 for electric blink reflexes) when using either (1) a first-order resistor–capacitor filter with a time constant of 50 or 100 ms, (2) a boxcar filter averaging 51 or 101 data points, or (3) an unequal-weight finite impulse response filter with a cutoff frequency of 5 or 10 Hz. These filters are thus recommended when determining peak amplitude. Applying a baseline correction on peak amplitude and integrated EMG produced slightly smaller values of R^2 compared with uncorrected measures.

1. Introduction

As explicated by Blumenthal et al. (2005), the human eyeblink reflex can be measured by recording the eyelid movement or the electromyographic (EMG) response of the orbicularis oculi muscle. In many studies, the blink reflex is measured as an index of central neural processes and their modification by psychological factors. In these studies, in which the kinematic aspects of the eyeblink are not of primary interest, recording the EMG response with surface electrodes is by far the most frequently used technique. After band-pass filtering of the raw EMG signal to remove low-frequency and high-frequency artifacts, two different procedures are generally followed for quantification of the EMG response magnitude: (1) mathematical integration of the rectified EMG signal (determining the area under the curve) within a certain time window after eliciting-stimulus onset; (2) determining the maximum value of the rectified signal within this time window (for an overview of signal processing procedures, see Blumenthal et al., 2005). Following the second method, the rectified signal is usually initially smoothed (low-pass filtered) to reduce random variations in the signal. A survey of 100 recent (2006–2009) acoustic or electric blink reflex studies from different disciplines – but the large majority from the behavioral sciences – shows that in 6 studies the EMG response was integrated whereas in 94 studies the maximum value of the rectified signal was determined.[1] In 18 studies of the latter group, the maximum value of the unsmoothed rectified signal was determined. In the other 76 studies, the rectified signal was first smoothed using either a resistor–capacitor (RC) circuit (43 studies), a nonrecursive (or finite impulse response, FIR) filter (25 studies), a recursive (or infinite impulse response, IIR) filter (3 studies), or an unspecified filter (5 studies). The time constant of the applied RC filters varied between 5 and 200 ms. The applied FIR filters largely consisted of simple equal-weight, or boxcar, filters calculating a moving average (23 out of 25 studies), the number of data points being averaged varying between 3 and 40. The large majority of all these studies did not present a rationale for calculating either the integrated EMG response or the peak amplitude. Also, several investigators used different methods in different studies. There appears thus to be not much consistency in the application of blink reflex magnitude quantification methods. The prevailing practice within behavioral studies to measure EMG peak amplitude seems, at least partly, based on early studies introducing this method. Some frequently used scoring programs (e.g., Balaban et al., 1986; see also Anthony and Graham, 1985) were designed for scoring either EMG, electrooculographic, or mechanical (potentiometric) blink reflex measures. These programs invariably scored peak amplitude of each response measure. Based on this convention, many current programs for scoring blink reflex EMG data, including several commercial systems, only provide the peak amplitude option or implicitly recommend applying this option (see also Berg and Balaban, 1999). In their guidelines for the elicitation, recording, and quantification of blink reflexes, Blumenthal et al. (2005) did not recommend a specific quantification method due to a lack of empirical data comparing different methods.

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[1] The results of this survey can be obtained from the author on request.

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Although it may be expected that the outcomes of signal integration and peak amplitude measurement are positively related, it remains unclear how strong these interrelations are. Grillon and Davis (1995) found that the mean within-subjects coefficient of determination (R^2) between integrated EMG and peak amplitude of the unsmoothed rectified signal was .85. Correlating integrated EMG with peak amplitude of either the unsmoothed or the smoothed rectified signal (using an RC filter with a time constant of 10 or 100 ms), Blumenthal (1998) found that the mean within-subjects R^2 varied between .56 and .88. Although the outcomes of the two methods are thus positively related, Blumenthal's data also suggest that the proportion of unshared variance may be considerable. The question thus rises which quantification method should be preferred.

This question can only be answered if a valid criterion exists for the magnitude of the blink reflex which may serve as a standard for evaluating other magnitude measures. I think that this criterion should be derived from the natural function of the blink reflex. Although the blink reflex strictly cannot be considered a nociceptive reflex (Ellrich et al., 2001), it is generally assumed that its primary function is protecting the eyeball in emergency situations. This implies that the criterion should be based on the effectiveness of the protective kinematic eyelid response. This effectiveness can be defined in terms of the amplitude and the maximum velocity of eyelid closure, both properties being linearly related (Evinger et al., 1991; Van der Werf et al., 2003). Reflexive eyelid closure is achieved by two tightly coupled actions: primarily, contraction of orbicularis oculi and, secondarily, relaxation of levator palpebrae (Björk and Kugelberg, 1953; Van Allen and Blodi, 1962). The surface EMG response of orbicularis oculi consists of the summated action potentials of the activated motor units, individual units firing repeatedly and asynchronously at high rates (Dengler et al., 1982). The summated twitch contractions of the individual units jointly determine the amplitude and maximum velocity of the eyelid closure response. All activated motor units thus contribute to the magnitude of the mechanical blink reflex response. Accordingly, preliminary data of Van der Werf et al. (2003) show a positive relationship between integrated surface EMG and the amplitude of eyelid closure as recorded with a magnetic search coil. However, in this study within-subjects R^2's were on average not large because different types of blinks (spontaneous, voluntary, and reflex blinks; the last ones being elicited with electrical or air puff stimuli) were pooled in the analyses. In addition, reflex blinks were elicited using stimuli of a fixed intensity leading to a restricted range of response magnitudes and thus prohibiting a reliable estimation of the relationship between integrated EMG and mechanical response size. As far as I know, an adequate investigation including a wide range of blink response magnitudes is not available so that there is no direct empirical proof of integrated surface EMG as a valid criterion of blink reflex magnitude. Nevertheless, many other studies performed on striated muscles have produced convincing evidence that mechanical response properties are linearly related to integrated EMG activity. Under isometric conditions, linear, or nearly linear, relationships have frequently been found between integrated EMG and dynamic or static response force (e.g., Bronks and Brown, 1987; Lawrence and De Luca, 1983; Woods and Bigland-Ritchie, 1983). During rapid isometric contractions, response force was determined by both the mean amplitude and duration of EMG bursts (Bronks and Brown, 1987). But also during anisometric, anisotonic contractions (which are mechanically comparable to reflexive eyelid responses), linear relationships were obtained between integrated EMG and force or maximal velocity, R^2's ranging between .86 and .96 (Bouisset, 1973). Given these findings and many other results (e.g., De Luca, 1997; Gielen et al., 1985; Hof, 1984), it may be assumed that integrated EMG can be used as a standard for evaluating other EMG quantification methods, such as peak amplitude of unsmoothed or smoothed rectified EMG. Within other disciplines, like physiology or neurology, integrated EMG is considered the undisputed standard measure for expressing the magnitude of dynamic EMG bursts like blink reflexes (see, for example, Fig. 7 of Kimura et al., 1994). This is based on the rationale that muscular contractions are determined by all activated motor units and not only by the unit, or subset of units, that accidentally discharge(s) at the single moment at which the EMG signal attains its instantaneous maximum. The surface EMG signal is a stochastic signal, implying that the magnitude of an EMG response can only be reliably quantified by averaging the signal over a certain epoch, that is, calculating the integrated EMG response. Due to these random variations, the instantaneous peak amplitude of the unsmoothed rectified blink reflex EMG burst will be much more sensitive to random error than the integrated value of the entire EMG burst. The implication is that a less reliable estimation of the real blink reflex magnitude is obtained, leading to larger within-subjects and between-subjects error components. As a consequence, a smaller effect size may be expected in studies in which the blink reflex is used as an index of psychological constructs (e.g., affective processes, attention, sensorimotor gating) and a smaller reproducibility of results within and between different laboratories. For these reasons, using integrated EMG as a measure of blink reflex magnitude can be recommended under all circumstances, despite the predominance of peak amplitude measurements in the recent literature as apparent from my survey. Nevertheless, investigators may prefer continuing measuring peak amplitude rather than measuring integrated EMG due to practical reasons such as available equipment or analysis programs or compatibility with earlier studies. Also, peak amplitudes may be measured to combine them with measurements of peak latency (e.g., Braff et al., 1999; Meincke et al., 2005; Swerdlow et al., 1995). When investigators for some reason prefer to use peak amplitude as a measure of blink reflex magnitude, random error associated with this measure can be substantially reduced, or perhaps completely eliminated, by adequately smoothing the rectified EMG signal. It would therefore be important to investigate if there are smoothing filters with outcomes equivalent to those of mathematical integration. A systematic comparison between integrated EMG and peak amplitude outcomes of different smoothing filters was therefore undertaken to identify the most appropriate filters. The validity of this comparison is limited insofar as it is presumed that processing of the raw EMG signal is accomplished according to the recommendations presented by Blumenthal et al. (2005).

Another issue related to blink reflex magnitude quantification is whether integrated EMG or peak amplitude should be corrected for the average EMG level during a short baseline period preceding or immediately following eliciting-stimulus onset. From the 6 studies that measured integrated EMG, only one study performed such a baseline correction. From the 94 studies that measured peak amplitude, 56 studies performed a baseline correction whereas in the other studies the absolute, uncorrected peak amplitude was measured. To evaluate the influence of baseline EMG activity in the current study, a comparison between peak amplitude and integrated EMG was performed for both uncorrected and baseline-corrected measures.

2. Method

2.1. Participants

The current analyses were applied on data that were collected in an earlier study (van Boxtel et al., 1998). Acoustic or electric blink reflexes were elicited in two different groups of 15 participants, each consisting of healthy students and staff members of Tilburg

University (mean ages being 25.3 and 20.3 years, respectively). The subjects were sitting upright on a chair behind a table in a sound-proof cabin which was electrically shielded by a Faraday cage. They were looking through a window at an animated cartoon presented on a computer monitor placed 95 cm in front of them outside the Faraday cage. This cartoon was merely used as a filler task to control the subjects' behavior. They were requested to fixate their eyes on a small spot located in the center of the monitor.

2.2. Stimulation and recording

In both stimulation conditions, 50 blink reflexes were elicited at irregular intervals varying between 15 and 20 s with a mean duration of 17.5 s. In the acoustic condition, a broadband noise burst with an intensity of 95 dB(A), a duration of 50 ms, and a rise/fall time smaller than 1 ms was generated by means of a Soundblaster 16MultiCD (Creative Labs) in combination with an electronic gate to suppress background noise and was presented binaurally via headphones (AKG, Model K100). Electrical blinks were elicited by means of an isolated stimulator (Devices, Model 2533) in series with a constant current unit (Grass, Model CCU-1). A rectangular current wave of 0.1 ms duration was applied transcutaneously to the supra-orbital branch of the trigeminal nerve in the right side of the face via two Ag/AgCl electrodes (2 mm contact area diameter), the cathode being placed near the supra-orbital foramen and the anode 2 cm above the cathode. Shock intensity was individually adjusted to obtain a clear R2 response and ranged between 12 and 20 mA.

Reflex EMG responses were recorded bipolarly from the inferior orbital part of the right orbicularis oculi muscle using Ag/AgCl electrodes (2 mm contact area diameter), one electrode being placed vertically under the pupil in forward gaze and the other electrode 12 mm (center-to-center) lateral to the first one. The EMG signal was amplified, band-pass filtered (Butterworth filters; −3-dB high-pass cutoff frequency at 0.4 Hz and attenuation rate 31 dB per octave; −3-dB low-pass cutoff frequency of 520 Hz and attenuation rate 13.5 dB per octave), and digitized at a rate of 1000 Hz. The digitized signal was stored during a 350-ms epoch, starting 150 ms before stimulus onset. These 350-ms data segments were stored in a contiguous data file on which all further processing operations were performed.

2.3. Data analysis

Further band-pass filtering (28–500 Hz) was applied offline to the stored raw EMG data using a low-pass and a high-pass ideal frequency response (unequal-weight) FIR filter with 1001 coefficients tapered with a Hamming window.[2] This frequency range was chosen for maximal removal of low-frequency and high-frequency artifacts while maximally retaining the true EMG signal (van Boxtel et al., 1998; see also Blumenthal et al., 2005).

Following rectification, EMG signals were smoothed using different low-pass filter types: (1) RC filters with a time constant of 5, 10, 20, 50, or 100 ms (corresponding to −3-dB low-pass cutoff frequencies of 32, 16, 8, 3.2, and 1.6 Hz, respectively); (2) boxcar filters averaging 5, 11, 21, 51, 101, or 201 data points (corresponding to −3-dB low-pass cutoff frequencies of 225, 90, 45, 18, 9, and 4.5 Hz, respectively); (3) ideal frequency response (unequal-weight) FIR filters with a low-pass cutoff frequency of 5, 10, 20, 30, 40, 50, or 60 Hz and 101 or 201 filter coefficients (except for the 5-Hz filter which could only be implemented using 201 coefficients).

Unsmoothed rectified EMG activity was integrated within a time window of 20–150 ms after stimulus onset for acoustic blink reflexes and 25–150 ms for electrical blink reflexes. These time windows were based on visual inspection of the raw EMG signals and on normative data for response latency and duration in healthy subjects which were collected in earlier studies (Ellrich and Hopf, 1996; Tackmann et al., 1982). The time window for analysis of the electric blink reflex was started 5 ms later than that for acoustic blinks to avoid influences of the electric R1 component (which has onset and offset latencies ranging between 9 and 24 ms). Although a time window terminating at 90 ms following stimulus onset will be adequate for analysis of the acoustic blink and the electrical R2 component, a longer window extending to 150 ms after stimulus onset (which conforms to the recommendations by Blumenthal et al., 2005) was used to accommodate for the analysis of an electrical R3 component or its acoustic counterpart. This late response component occasionally occurs in some subjects, particularly following strong electrical (Boelhouwer et al., 1991; Ellrich et al., 2001) or acoustic stimuli (Brown et al., 1991; Meincke et al., 2005) and is considered by some investigators as representing the real startle response in orbicularis oculi (e.g., Brown et al., 1991; Ellrich and Hopf, 1996). This component is not frequently observed because it quickly habituates (Rossi et al., 1989) and is readily abolished under the influence of attention to the eliciting stimulus (Ellrich and Hopf, 1996; Rossi et al., 1993).

Peak amplitudes of unsmoothed and smoothed rectified EMG responses were determined within the same time windows as were used for calculating integrated EMG responses. Peak amplitudes were also corrected by subtracting the average EMG amplitude (i.e., the mean rectified voltage) determined during a 50-ms baseline period preceding stimulus onset. A similar correction was performed for integrated EMG values (after transforming them into mean rectified voltage to make them compatible with the baseline amplitude metric). For each subject, uncorrected and baseline-corrected peak amplitude values were correlated with uncorrected and baseline-corrected integrated EMG values, respectively. Within-subject correlations were transformed into Fisher's z values and averaged across subjects. Mean z values were transformed into mean R^2 values.

Based on visual inspection of band-pass filtered raw EMG data, the data of two subjects in the acoustic stimulation condition were removed due to absent reflex responses during 10 or more trials. In the same condition, one subject had two and another one had five trials with zero values. None of the other subjects in this condition and the subjects in the electric condition did have trials with zero values. Of all trials in the acoustic and electric conditions, 2.3 and 3.3% were deleted, respectively, due to the presence of spontaneous blinks or voluntary dynamic contractions preceding or following the blink response analysis window.

3. Results

The first important question is whether smoothing of the rectified EMG signal improves the reliability of peak amplitude as an estimate of integrated EMG. Peak amplitudes of smoothed EMG responses showed almost without exception a stronger relationship (R^2) with integrated EMG than peak amplitudes of unsmoothed EMG responses, both for uncorrected and baseline-corrected values during acoustic and electric stimulation conditions (Fig. 1).

The second question is which smoothing filters produce the strongest relationship between peak amplitude and integrated EMG. As can be seen in Fig. 1, both for acoustic and electric

[2] Filters designed with a Hamming tapering window were used for bandpass-filtering of raw blink EMG responses and for smoothing of rectified blink EMG responses. This window type results in a relatively narrow transition band and relatively good suppression of ripple in passband and stopband (cf. Cook and Miller, 1992; Nitschke et al., 1998). A general advantage of FIR-filters is that they do not introduce frequency-dependent phase shifts in the input EMG signal and thus do not distort the signal.

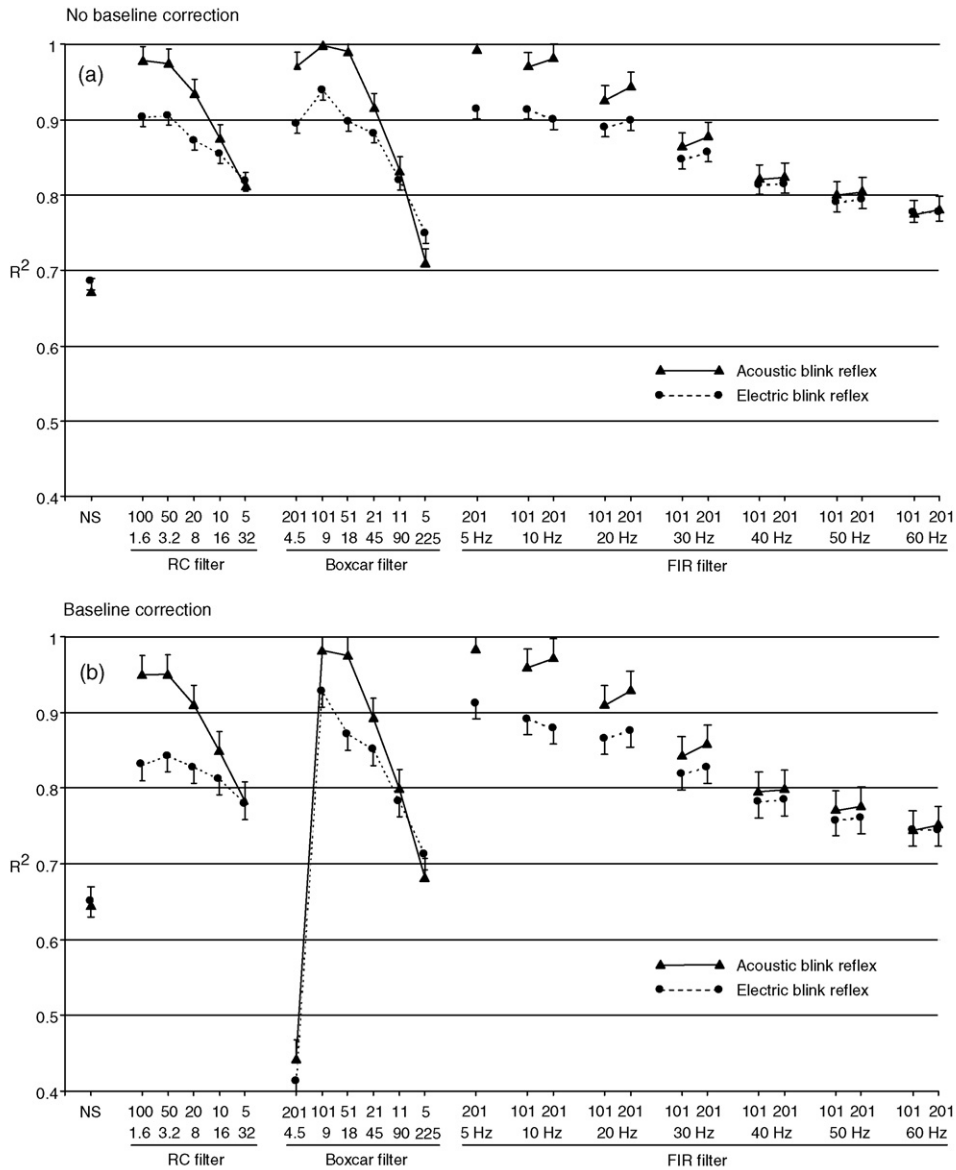

Fig. 1. Mean (±standard error) within-subjects relationship (R^2) between (a) integrated blink reflex EMG responses and (b) peak amplitudes of unsmoothed (NS: no smoothing) or smoothed rectified EMG responses using different smoothing filters: (1) RC filter with a time constant varying between 5 and 100 ms, the corresponding cutoff frequencies varying between 32 and 1.6 Hz; (2) boxcar filter averaging from 5 to 201 data points, the corresponding cutoff frequencies varying between 225 and 4.5 Hz; (3) unequal-weight FIR filter with either 101 or 201 filter coefficients and a cutoff frequency varying between 5 and 60 Hz. Separate analyses were performed for uncorrected and baseline-corrected values of integrated EMG and peak amplitude.

reflexes, mean R^2 generally increased when using (a) an RC filter with a longer time constant, (b) a boxcar filter averaging over a larger number of data points (with the exception of 201 points), and (c) a FIR filter with a lower low-pass cutoff frequency, the number of filter coefficients (either 101 or 201) having no substantial influence. During acoustic stimulation, both for uncorrected and baseline-corrected conditions, R^2 was at least .95 when using either an RC filter with a time constant of 50 or 100 ms, a boxcar filter averaging 51 or 101 data points, or a FIR filter with a 5-Hz cutoff frequency (and 201 coefficients) or a 10-Hz cutoff frequency (and 101 or 201 coefficients). Also for electric reflexes, the output of these seven filters provided an almost perfect linear relationship with integrated EMG although the values of R^2 were systematically lower than in the acoustic condition, being at least .90 for uncorrected values and .83 for baseline-corrected values.

Another question in this study is whether baseline correction affects the reliability of peak amplitude as an estimate of integrated EMG. As illustrated in Fig. 1, mean differences in R^2 were generally small but in some cases correlations were nevertheless significantly larger for uncorrected than for baseline-corrected measures. During the acoustic stimulation condition, a *t*-test for correlated samples revealed significantly larger Fisher's *z* values for uncorrected measures when using either (a) an RC filter with a time constant of 50 ms, $t(12) = 2.45$, $p < .05$, or 100 ms, $t(12) = 3.21$, $p < .01$, (b) a boxcar filter averaging 51 data points, $t(12) = 2.68$, $p < .05$, 101 data points, $t(12) = 7.01$, $p < .001$, or 201 data points, $t(12) = 8.38$, $p < .001$, or (c) a 5-Hz FIR filter with 210 coefficients, $t(12) = 4.16$, $p < .01$. During the electric stimulation condition, significantly larger correlations were found for uncorrected than for baseline-corrected values when EMG responses were not smoothed, $t(14) = 3.12$, $p < .01$, or were smoothed using either

(a) an RC filter with a time constant of 5 ms, $t(14) = 2.17$, $p < .05$, 10 ms, $t(14) = 2.21$, $p < .05$, 50 ms, $t(14) = 3.49$, $p < .01$, or 100 ms, $t(14) = 4.32$, $p < .001$, or (b) a boxcar filter averaging 201 data points, $t(14) = 9.34$, $p < .001$. When considering the seven optimal filters mentioned above, R^2 was in the acoustic condition on the average .98 and .97 for uncorrected and baseline-corrected values, respectively. In the electric condition, these values were .91 and .88, respectively, confirming that the overall effect of baseline correction was small.

4. Discussion

This study was undertaken to evaluate the performance of different filters for smoothing rectified blink reflex EMG signals using the integrated EMG response as a criterion, assuming that integrated EMG best represents the functional (i.e., kinematic) aspects of the blink reflex. If a smoothing filter has an effect that peak amplitude of rectified EMG approaches integrated EMG, such a filter may be supposed to sufficiently reduce the random error component inherent to peak amplitude to make it a useful alternative to integrated EMG. Although integrated EMG theoretically remains the most reliable index of blink reflex EMG responses, some smoothing filters may thus be considered to produce equivalent results.

The current analyses show that peak amplitude of smoothed rectified EMG shows an almost perfect relationship with integrated EMG when using one of the seven specific filters recommended in this study, irrespective of which filter is used. Apart from these particular filters, the results suggest that in general a better performance (i.e., a more efficient estimation of the true blink reflex magnitude) may be expected when using either (a) an RC filter with a longer time constant, (b) a boxcar filter averaging over a larger number of data points, or (c) a FIR filter with a lower low-pass cutoff frequency since these manipulations uniformly result in a systematic decrease in random error of peak amplitude as an estimate of the compound motor unit activity throughout a blink reflex EMG burst.

Nevertheless, the results also suggest that there is a restriction to this rule. The effectiveness of a boxcar filter showed a seemingly paradoxical decrease when the number of coefficients was increased from 101 to 201 (this decrease was particularly strong when a correction was made for baseline activity but this more complicated situation will be discussed below). An explanation is that filters with a larger number of coefficients have a smaller resolution in the time domain (Cook and Miller, 1992). Practically, this means that the larger the number of coefficients, the greater the probability that the output signal (and thus peak amplitude) is influenced by potentials outside the blink response analysis window, such as preceding baseline activity or, in case of electric stimulation, the electric stimulation artifact and R1 potential. The stronger such extraneous influences, the smaller will be the correlation between peak amplitude and integrated EMG. Given a sample frequency of 1000 Hz, peak amplitude estimates will be much less strongly influenced by adjacent potentials when using a boxcar filter with 101 coefficients than when using a filter with 201 coefficients. The reason is that in the former case, influences of adjacent potentials are limited to an interval of 50 ms preceding peak response (see Nitschke et al., 1998, p. 55) whereas acoustic and electric peak response latencies are usually a little longer than 50 ms so that disturbing effects of baseline activity or a large electric stimulation artifact on peak amplitude estimation are prohibited. When using a filter with 201 coefficients, peak amplitude estimation is influenced by adjacent potentials within a 100-ms interval preceding peak response, including baseline activity, electric stimulation artifact, and R1 potential. The negative effect of increasing the number of coefficients from 101 to 201 on filter performance obviously did not occur for the FIR filter since R^2's did not systematically diminish when increasing the number of coefficients. This can be explained by the fact that the impact of adjacent potentials on blink reflex peak amplitude will be much smaller for (unequal-weight) FIR filters than for (equal-weight) boxcar filters. The reason is that all coefficients of a boxcar filter function have the same value (weighting adjacent potentials as strongly as blink response potentials) whereas a FIR filter function consists of a central main lobe with relatively large filter coefficients surrounded by side lobes with much smaller coefficients declining to zero when approaching the extremes of the function. Using a FIR filter, adjacent potentials will thus have a smaller effect on blink reflex peak amplitude estimation than when using a boxcar filter because their contribution is much less stronger weighted in the filter output signal.[3] The influences from adjacent potentials in the time domain on blink reflex peak amplitude estimates imply that the number of stored data points should be proportional to the number of filter coefficients. If an equal-weight or unequal-weight FIR filter has $2j + 1$ coefficients, at least j data points should precede and follow the signal epoch of interest (see Cook and Miller, 1992, p. 367).

Although an RC filter with a time constant of 50 or 100 ms appears to be more effective than RC filters with a shorter time constant, the time domain resolution principle suggests that a time constant longer than 100 ms may be less effective than shorter time constants. However, the choice of the optimal time constant may be more complicated when using an analog, rather than a digital, RC filter. As demonstrated by Blumenthal (1994), increasing the time constant of an analog RC filter attenuates the peak amplitude of the output signal which may result in a failure to detect small responses and, therefore, an overestimation of the proportion of participants without a measurable blink reflex. This was one of Blumenthal's arguments to recommend using a time constant of 10 ms (see also Blumenthal et al., 2005). However, in Blumenthal's study, EMG responses were rectified and analog filtered before they were digitized. Digitizing low-amplitude signals using an analog-to-digital converter with a limited resolution (e.g., a 12-bit converter) may lead to poor detection of small peak responses as well as poor discrimination between responses of different magnitude (see also Blumenthal et al., 2005, p. 7). The current results show that such a loss of sensitivity associated with using a long time constant does not occur when digital filtering is applied following digitization instead of preceding it.

It may seem remarkable that a simple boxcar filter with 51 or 101 coefficients appeared to be at least as effective as more sophisticated unequal-weight FIR filters. However this is not surprising given the fact that a boxcar filter attenuates all frequency components except 0 Hz, the attenuation becoming stronger with an increasing number of coefficients (Cook and Miller, 1992). This means that with an increasing number of coefficients, the output culminates in the dc level of the rectified signal, whereas the dc level is proportional to the integrated EMG value. Although a boxcar filter has a very poor frequency precision, it seems thus an ideal solution for the limited purpose of estimating integrated EMG activity.

The current results show that the same filters are optimal for smoothing acoustic and electric blink reflexes, although R^2's in the

[3] The time domain resolution principle also explains why an unequal-weight FIR filter with a 2-Hz low-pass cutoff frequency – requiring at least 501 filter coefficients given a sample frequency of 1000 Hz – appeared to be less effective than the tested 5 or 10-Hz filters. On the other hand, FIR filters with 51 or a smaller number of coefficients neither appeared to be more effective, nor were even less effective, than filters with 101 or 201 coefficients. This can be explained by the fact that a smaller number of coefficients is associated with a smaller resolution in the frequency domain (i.e., a wider transition band), and thus less effective removal of high-frequency components representing random error. The results of these additional tests are not reported in detail.

majority of cases were lower for electric reflexes. This difference can be explained by preliminary potentials, such as the stimulation artifact and R1 component, which add random error to the estimation of the R2 peak response. Recording electric blink reflexes contralaterally to the site of electrical stimulation might decrease this error component because in that condition the R1 component is avoided (although the stimulation artifact remains present).

It was also found that baseline correction, although being used in the majority of studies surveyed, did not have substantial effects compared to uncorrected values (except in the case of using a boxcar filter with 201 coefficients; see below). Both for acoustic and electric blink reflexes, correlations between peak amplitude and integrated EMG were generally somewhat smaller with than without correction, but only for a subset of filters these differences were significant, although also in these cases being small. The implicit assumption underlying baseline correction is that blink reflex magnitude is positively influenced by the level of sustained background EMG activity. For electrical blink reflex responses, it has indeed been demonstrated that R1 and R2 components are increasingly potentiated during sustained voluntary orbicularis oculi contractions of increasing strength (Jäncke et al., 1994; Sanes, 1984; Sanes and Ison, 1980). Subtracting baseline EMG activity from peak amplitude and integrated EMG (expressed as mean rectified voltage) would at least partially compensate for the potentiating effect of sustained contraction. Nevertheless, as this subtraction is similar for both response magnitude measures, it may not be expected to have a substantial influence on the correlation between the two measures. As a single exception, baseline correction led to an exceptionally strong decrement in R^2 when using a boxcar filter with 201 coefficients. Using such a wide smoothing filter has not only as an effect that peak amplitude estimation is affected by preceding potentials (as was earlier explained) but, reversely, also that baseline activity estimation is influenced by the magnitude of blink reflex potentials. This additional random error component in the two estimates makes their difference score also less reliable, resulting in a much lower correlation between this score and the difference score calculated for integrated EMG and being responsible for the strong decrement in R^2 when using a boxcar filter with 201 coefficients.

I think that on the basis of these results it is difficult to draw a definite conclusion about the utility of baseline correction because baseline potentials are not only determined by background EMG activity but also by the noise of the recording system. Working in an electrically shielded environment, the effect of noise was limited in this study so that it is difficult to generalize the current results regarding baseline correction to other environments.

In conclusion, the relationship between peak amplitude of smoothed rectified EMG and integrated EMG activity as indices of the magnitude of acoustic or electric blink reflexes shows considerable variability depending on the type of smoothing filter that is applied. However, when using specific filters (i.e., an RC filter with a time constant of 50 or 100 ms; a boxcar filter averaging 51 or 101 data points; or an unequal-weight FIR filter with either a 5-Hz cutoff frequency and 201 coefficients, or a 10-Hz cutoff frequency in combination with 101 or 201 coefficients), an almost perfect relationship between both response measures is achieved, independently of whether or not a correction is made for differences in the level of baseline EMG activity.

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