# Choosing smoothness parameters for smoothing splines by minimizing an estimate of risk

Rafael A. Irizarry

*Department of Biostatistics, Johns Hopkins University*

615 N. Wolfe Street, Baltimore, Maryland 21205

rafa@jhu.edu, 410-614-5157, 410-955-0958 (fax)

SUMMARY. Smoothing splines are a popular approach for non-parametric regression problems. We use periodic smoothing splines to fit a periodic signal plus noise model to data for which we assume there are underlying circadian patterns. In the smoothing spline methodology, choosing an appropriate smoothness parameter is an important step in practice. In this paper, we draw a connection between smoothing splines and REACT estimators that provides motivation for the creation of criteria for choosing the smoothness parameter. The new criteria are compared to three existing methods, namely cross-validation, generalized cross-validation, and generalization of maximum likelihood criteria, by a Monte Carlo simulation and by an application to the study of circadian patterns. For most of the situations presented in the simulations, including the practical example, the new criteria out-perform the three existing criteria.

KEY WORDS: Non-parametric smoothing, REACT estimators, Smoothing splines, Smoothness parameter.

# 1 Introduction

Most organisms generate physiological and behavioral measurements with oscillations (Refinetti and Menaker 1992). It is quite common for these oscillations to have a 24 hours period. In this case, we refer to them as *circadian patterns* or *circadian rhythms*. Various researchers have used statistical models to describe data believed to contain circadian patterns, see for example Greenhouse, Kass,and Tsay (1987) and Wang and Brown (1996). Modeling circadian patterns can have practical applications, for example Irizarry et al. (2001) used circadian pattern estimates to assess homeostasis in mice. In general, one is interested in describing circadian patterns as smooth functions of times but the data used to estimate these patterns usually contains noise. The problem of estimating circadian shapes is commonly viewed as a non-parametric regression problem.

Smoothing splines are a popular approach for non-parametric regression problems. For example, the widely used S-Plus function `gam()` uses local regression `lo()` and smoothing splines `s()` as built-in smoothers (Hastie 1993). Many authors, Schoenberg (1964), Reinsch (1967), Wahba and Wold (1975), and Silverman (1985) to name a few, have studied smoothing splines and demonstrated desirable theoretical properties. Some, for example Rice and Rosenblatt (1983), have developed asymptotic results for smoothing splines. For a good review of spline methods in statistics see Eubank (1988) and for a complete theoretical treaty see Wahba (1990).

When using smoothing splines one does not need to choose the location of knots and the smoothness of the estimate is controlled via one parameter, usually referred to as the smoothness parameter and denoted in this paper with $\lambda$. This makes the procedure easy to implement in practice. In Section 2 we describe smoothing splines in more detail.

Choosing an appropriate $\lambda$ is an important step in practice. A $\lambda$ that is "too close to zero" will yield an estimate practically equivalent to the data, and a $\lambda$ that is "too big" will produce an estimate practically equivalent to the linear regression estimate of the data. Cross validation (CV) and generalized cross-validation (GCV) (Craven and Wahba (1979)) are popular approaches for finding an appropriate criterion and are the two procedures available through the S-Plus function `smooth.spline()`. These procedures have been criticized for choosing $\lambda$s that are "too small" (Hastie and Tibshirani, page 52) and other approaches have been proposed, for example Wahba's (1985) Generalized Maximum Likelihood (GLM) criterion. In Section 3, for a regular time series periodic signal plus noise model, we establish a connection between smoothing splines and Beran's (2000) Risk Estimation After Coordinate Transform (REACT) estimators and use it to motivate a new criterion for choosing the smoothness parameter. As described in Section 4 this new method, which we will refer to as the REACT criterion for choosing the smoothness parameter, is convenient from a computational perspective. Furthermore, we compare its performance by comparing mean squared error (MSE), through a Monte Carlo simulation, to CV, GCV, and GLM. In Section 5 we compare the methods through a real-data example.

## 2 Smoothing splines

Consider the signal plus noise model

$$y_i = s(t_i) + \varepsilon_i, i = 1, \ldots, n, t_1 < \ldots < t_n \in [0, 1] \tag{1}$$

where $\boldsymbol{\varepsilon} = (\varepsilon_1, \ldots, \varepsilon_n)' \sim N(0, \sigma^2 \mathbf{I}_{n\times n})$, $\sigma^2$ is unknown and $s$ some function in the so-called Sobolev Hilbert space of functions $W_2^m[0, 1]$ with domain $[0, 1]$, the derivatives $s^{(l)}, l = 1, \ldots, m-1$ absolutely continuous, and bounded $s^{(m)}$. In practice, $s(t)$ can represent the underlying circadian pattern and $\varepsilon$ represents measurement error and environmental variation.

We will denote $\mathbf{y} = (y_1, \ldots, y_n)'$ and, to follow Beran's (2000) notation, $\boldsymbol{\eta} = \{s(t_1), \ldots, s(t_n)\}'$. The smoothing spline estimate is defined as the function $\hat{s}_\lambda \in W_2^m[0, 1]$ yielding the $\hat{\boldsymbol{\eta}}_\lambda$ that minimizes a penalized least squares criterion,

$$\frac{1}{n}|\mathbf{y} - \boldsymbol{\eta}|^2 + \lambda \int_0^1 \{s^{(m)}(u)\}^2 \, du \tag{2}$$

with $|\mathbf{y} - \boldsymbol{\eta}|^2 = \sum_{i=1}^n \{y_i - s(t_i)\}^2$. Throughout the text we will be using the hat notation, for example $\hat{\boldsymbol{\xi}}$, to denote estimates in general. In different parts of the text the meaning of, say, $\hat{\boldsymbol{\xi}}$ changes. However, the meaning should be clear from the context.

For $m = 2$, Reich (1967) proved that, given a $\lambda$, the solution to minimizing (2) is a natural cubic spline with knots at $t_1, \ldots, t_n$. This implies that we can write the $\boldsymbol{\eta}$ that minimizes (2) as $\hat{\boldsymbol{\eta}}_\lambda = \mathbf{N}(\mathbf{N}'\mathbf{N} + \lambda\boldsymbol{\Omega})^{-1}\mathbf{N}\mathbf{y}$ where $\mathbf{N}$ and $\boldsymbol{\Omega}$ are $n \times n$ matrices defined by the basis functions for the space of natural cubic splines with knots at $t_1, \ldots, t_n$ (see Buja, Hastie, and Tibshirani 1989). Using basic matrix algebra tricks we can find $n \times n$ matrices $\mathbf{U}$ and $\mathbf{\Lambda}$, with $\mathbf{\Lambda}$ diagonal, such that we can re-write $\hat{\boldsymbol{\eta}}$ as

$$\hat{\boldsymbol{\eta}}_\lambda = \mathbf{U}(\mathbf{I}_{n\times n} - \lambda\mathbf{\Lambda})^{-1}\mathbf{U}'\mathbf{y} \tag{3}$$

Notice $(\mathbf{I}_{n\times n} - \lambda\mathbf{\Lambda})^{-1}$ is a diagonal matrix and later we denote the vector of diagonal entries as $\mathbf{f}(\lambda)$.

Becuase of the nature of the data described in Section 5 and because circadian patterns are periodic we consider the case of periodic smoothing splines for regular time series with equally spaced knots. Furthermore, describing the REACT methodology for choosing the smoothness parameter can be done in a simple fashion for this case. However, in Section 6 we describe how this method can be extended to the general case is a straight-forward way.

## 2.1 Periodic smoothing splines

In this section we consider the case where $s \in W_2^m[0,1]$ is periodic, i.e. $s(0) = s(1)$ and $s^{(l)}(0) = s^{(l)}(1), l = 1,\dots,m$, and the data is a regular time series, i.e. $t_i = i/n, i = 1,\dots,n$. As noted by Wahba (1990), for a given $\lambda$, the periodic function in $W_2^m[0,1]$ that minimizes (2) is well approximated by a function of the form

$$s_\lambda(t) = a_0 + \sum_{j=1}^{n/2-1} a_j\sqrt{2}\cos(2\pi jt) + \sum_{j=1}^{n/2-1} b_j\sqrt{2}\sin(2\pi jt) + a_{n/2}\cos(\pi nt). \tag{4}$$

Let $\mathbf{U}_{DFT}$ be the $n\times n$ orthogonal discrete Fourier transform (DFT) matrix defined by

$$U_{i,1} \;=\; \{n^{-1/2}\}, i = 1,\dots,n$$

$$
\begin{aligned}
U_{i,2j} &= \{(2/n)^{1/2} \cos(2\pi j \; t_i)\}, i = 1, \ldots, n, j = 1, \ldots, n/2 - 2 \\
U_{i,2j+1} &= \{(2/n)^{1/2} \sin(2\pi j \; t_i)\}, i = 1, \ldots, n, j = 1, \ldots, n/2 - 1 \\
U_{i,n} &= \{n^{-1/2} \cos(\pi i)\}, i = 1, \ldots, n \qquad (5)
\end{aligned}
$$

and denote $\mathbf{z} = \mathbf{U}'_{DFT}\mathbf{y}$ and $\boldsymbol{\xi} = \mathbf{U}'_{DFT}\boldsymbol{\eta}$. Notice that $\mathbf{z}$ is the spectral decomposition of $\mathbf{y}$. We can use Fourier's theorem to show that for functions of the form (4), minimizing (2) is equivalent to minimizing

$$
\frac{1}{n}|\mathbf{z} - \boldsymbol{\xi}|^2 + \frac{\lambda}{n}\left\{\sum_{j=1}^{n/2-1}(a_j^2 + b_j^2)(2\pi j)^{2m} + \frac{1}{2}a_{n/2}^2(\pi n)^{2m}\right\} \qquad (6)
$$

with $|\mathbf{z}-\boldsymbol{\xi}|^2 = \sum_{j=0}^{n/2}(a_j-\hat{a}_j)^2+\sum_{j=1}^{n/2-1}(b_j-\hat{b}_j)^2$, where $(\hat{a}_0, \hat{a}_1, \hat{b}_1, \ldots, \hat{a}_{n/2-1}, \hat{b}_{n/2-1}, \hat{a}_{n/2}) \equiv \mathbf{z}$, and easily show that the value $\boldsymbol{\xi}$ that minimizes (6) is $\mathbf{f}(\lambda)\mathbf{z}$, with $\mathbf{f}(\lambda)$ a $n-$dimensional vector and the multiplication component-wise (as in S-Plus or matlab). Furthermore, taking the derivative of (6) and solving for 0 gives us, what we will call, the *shrinkage coefficients* $\mathbf{f}(\lambda) = \{f_0, f_1(\lambda), f_1(\lambda), \ldots, f_{n/2-1}(\lambda), f_{n/2-1}(\lambda), f_{n/2}(\lambda)\}'$ in closed-form, with

$$
f_0 = 1, f_j(\lambda) = \{1+\lambda(2\pi j)^{2m}\}^{-1}, j = 1, \ldots, \frac{n}{2}-1, f_{n/2}(\lambda) = \{1+0.5\lambda(\pi n)^{2m}\}^{-1}. \quad (7)
$$

Because $\mathbf{U}_{DFT}$ is an orthonormal transformation we have that the estimator that minimizes (2) is $\mathbf{U}_{DFT}\mathbf{f}(\lambda)\mathbf{z}$.

Notice that we are assuming that $n$ is even. This is done without loss of generality. If $n$ were odd, all the above remains the same except $n/2 - 1$ becomes $(n-1)/2$ and the terms indexed by $n/2$ are ignored.

In summary, we have noticed that for a regular time series periodic signal plus noise model, the smoothing spline estimate of $s$, for a given $\lambda$, can be well approximated by $\mathbf{U}_{DFT}\text{diag}[\mathbf{f}(\lambda)]\mathbf{U}'_{DFT}\mathbf{y}$ and we have closed form expressions for $\mathbf{U}_{DFT}$ and $\mathbf{f}(\lambda)$. This can be viewed as "filtering" the data $\mathbf{y}$ using a filter defined by the $\mathbf{f}$ which are in turn defined by $\lambda$ and the smoothing spline procedure.

As mentioned, choosing $\lambda$ is an important step in practice. A popular way of precisely defining an optimal $\lambda$ is to use the expected MSE or risk, that is to choose the $\lambda$ yielding the estimate $\hat{\boldsymbol{\eta}}_\lambda$ that minimizes

$$R(\hat{\boldsymbol{\eta}}_\lambda, \boldsymbol{\eta}, \sigma^2) = \frac{1}{n}\mathrm{E}|\hat{\boldsymbol{\eta}}_\lambda - \boldsymbol{\eta}|^2. \tag{8}$$

The CV and GCV criteria try to estimate the $\lambda$ that provides the smoothing spline estimate $\hat{\boldsymbol{\eta}}_\lambda$ that minimizes (8). In the following sections we describe the REACT criterion for choosing $\lambda$.

# 3 REACT

For data $\mathbf{y}$ arising from a model like (1), Beran (2000) studies the linear shrinkage estimates of $\boldsymbol{\xi} = \mathbf{U}'\boldsymbol{\eta}$ defined by $\{\hat{\boldsymbol{\xi}}(\mathbf{f}) \equiv \mathbf{fz}, \mathbf{f} \in [0,1]^n\}$ with $\hat{\boldsymbol{\xi}}(\mathbf{f})$ component-wise as in the previous section and $\mathbf{U}$ is an orthonormal basis transformation. This implies that the risks $R(\hat{\boldsymbol{\eta}}, \boldsymbol{\eta}, \sigma^2) = R(\hat{\boldsymbol{\xi}}, \boldsymbol{\xi}, \sigma^2)$ are identical, so a good estimate of $\boldsymbol{\xi}$ will provide an estimate for $\boldsymbol{\eta}$ that is just as good. In Beran's approach, the transformation $\mathbf{U}$ is chosen to be an *economical basis*. By economical basis we mean that we expect only the first few components of $\boldsymbol{\xi}$ to be much different from 0 in absolute value. If this is the case, we can reduce the risk by shrinking the higher components of $\mathbf{z}$ (the $z_i$s for which we expect $\xi_i$ to be close to 0) towards 0. Notice that for a specific component, the amount of bias we add, $(1 - f_i)^2\xi_i^2$ is small if $\xi_i$ is close to 0, and the variance is reduced by a factor of $f_i^2$, which is substantial if the amount of shrinkage is significant, i.e. $f_i$ is close to 0. Once an appropriate economical basis has been chosen, REACT is data-driven procedure that chooses a vector of shrinking coefficients $\hat{\mathbf{f}}$ that minimize an estimate of risk, and defines the REACT estimator of $\boldsymbol{\xi}$ as $\hat{\boldsymbol{\xi}}(\mathbf{f}) = \hat{\mathbf{f}}\mathbf{z}$. This implies $\hat{\boldsymbol{\eta}}(\hat{\mathbf{f}}) = \mathbf{U}\hat{\boldsymbol{\xi}}(\hat{\mathbf{f}})$ is the REACT estimate for $\boldsymbol{\eta}$. Beran (2000) describes ways to choose $\hat{\mathbf{f}}$ so that $\hat{\boldsymbol{\xi}}(\hat{\mathbf{f}})$ has desirable asymptotic properties.

Turning our attention back to periodic smoothing splines, from (5) notice that $\mathbf{U}_{DFT}$ has columns that are of increasingly higher frequency, i.e. columns of decreasing smoothness. If in fact $s$ is smooth, then only the first few components of $\boldsymbol{\xi} = \mathbf{U}'_{DFT}\boldsymbol{\eta}$ will be "much different" from zero in absolute value. For a given $\lambda$ we notice that the smoothing spline estimate can be thought of as a REACT estimator $\mathbf{U}_{DFT}\hat{\boldsymbol{\xi}}(\lambda)$ with $\mathbf{z} = \mathbf{U}'_{DFT}\mathbf{y}$ and $\hat{\boldsymbol{\xi}}(\lambda) = \mathbf{f}(\lambda)\mathbf{z}$ with the multiplication component-wise. Expression (7) shows that this estimate automatically shrinks the "high-frequency" components of $\boldsymbol{\eta}$. The bigger $\lambda$ the more we shrink. Now we will see how the ideas used to choose $\mathbf{f}$ in REACT estimation can be used to select appropriate $\lambda$s for smoothing splines.

For any $m \times 1$ vector $\mathbf{x}$, let $\mathrm{sum}(\mathbf{x}) = \sum_{i=1}^{m} x_i$ and $\mathrm{ave}(\mathbf{x}) = m^{-1}\mathrm{sum}(\mathbf{x})$ and notice we can write the risk of $\hat{\boldsymbol{\xi}}(f) = \mathbf{f}\mathbf{z}$ as

$$R(\hat{\boldsymbol{\xi}}(\mathbf{f}), \boldsymbol{\xi}, \sigma^2) = \text{ave}[\sigma^2 \mathbf{f}^2 + \boldsymbol{\xi}^2 \{1 - \mathbf{f}\}^2] \tag{9}$$

with the multiplication component-wise as before. Ideally, if we knew the risk function (9), we would estimate $\boldsymbol{\xi}$ with $\tilde{\mathbf{f}}\mathbf{z}$ with $\tilde{\mathbf{f}}$ the $\mathbf{f} \in [0,1]^n$ minimizing (9). However, this *ideal linear estimator* $\tilde{\boldsymbol{\xi}}$ is unrealizable in practice because $\boldsymbol{\xi}$ and $\sigma^2$ are unknown. Beran (2000) considers

$$\hat{R}(\hat{\boldsymbol{\xi}}(\mathbf{f}), \mathbf{z}, \hat{\sigma}^2) = \text{ave}[\{\mathbf{f} - \hat{\mathbf{g}}\}^2 \mathbf{z}^2] + \text{ave}[\hat{\sigma}^2 \hat{\mathbf{g}}], \tag{10}$$

with $\hat{\mathbf{g}} = 1 - \hat{\sigma}^2/\mathbf{z}^2$ and $\hat{\sigma}^2$ a "trust-worthy" estimator of $\sigma^2$, as a surrogate for the risk defined in (9) in identifying the best candidate estimators. Beran (2000) points out that the value $\mathbf{f} = \hat{\mathbf{g}}$ that minimizes (10) is inadmissible but that by restricting the space of $\mathbf{f}$s over which we minimize (10) we obtain estimates with desirable properties (see Beran and Dümbgen (1998) and Beran (2000) for details). If we restrict the space of $\mathbf{f}$s to vectors with the form defined by (7) and determined by $\lambda$ then our REACT estimator is equivalent to a smoothing spline estimate. Furthermore, these estimates have desirable asymptotic properties as described in the Appendix. This motivates, what we call, the REACT criterion for choosing smoothing parameters that works by constraining the $\mathbf{f}$ with (7), denoting it $\mathbf{f}(\lambda)$, and choosing $\lambda$ by

$$\hat{\lambda} = \arg \min_{\lambda \in [0,\infty]} \text{ave}[\{\mathbf{f}(\lambda) - \hat{\mathbf{g}}\}^2 \mathbf{z}^2], \tag{11}$$

with $\hat{\mathbf{g}}$ and $\hat{\sigma}^2$ defined as in (10). This in turn defines the estimates $\hat{\boldsymbol{\xi}}(\hat{\lambda}) = \mathbf{f}(\hat{\lambda})\mathbf{z}$ and

$\hat{\boldsymbol{\eta}}(\hat{\lambda}) = \mathbf{U}_{DFT}\hat{\boldsymbol{\xi}}(\hat{\lambda})$. Notice that for periodic smoothing splines we have

$$\begin{aligned}\text{ave}[\{\mathbf{f}(\lambda) - \hat{\mathbf{g}}\}^2\mathbf{z}^2] \;\propto\; & \sum_{j=1}^{n/2-1} \left\{ \left(1 - \frac{\hat{\sigma}^2}{\hat{a}_j}\right) - f_j(\lambda) \right\}^2 \hat{a}_j^2 + \sum_{j=1}^{n/2-1} \left\{ \left(1 - \frac{\hat{\sigma}^2}{\hat{b}_j}\right) - f_j(\lambda) \right\}^2 \hat{b}_j^2 \\ + \; & \left\{ \left(1 - \frac{\hat{\sigma}^2}{\hat{a}_{n/2}}\right) - f_{n/2}(\lambda) \right\}^2 \hat{a}_{n/2}^2. \qquad (12)\end{aligned}$$

and finding $\hat{\lambda}$ can be thought of as an example of estimating a parameter $\lambda$ using weighted least squares where our data are the *empirical shrinkage estimates* $\hat{\mathbf{g}}$. In Figure 1 we see plots showing an example of the function $\{1 + \lambda(2\pi j)^{2m}\}^{-1}$ fitted to $\hat{\mathbf{g}}$ and the weights used in the weighted least squares equation.

Obtaining $\hat{\lambda}$ is computationally simple. In S-Plus the $\hat{a}_j$s and $\hat{b}_j$s are obtained using the function `fft()` and minimizing (12) can be done with `ms()` or `nlminb()`. The final estimate $\hat{\boldsymbol{\eta}}$ can be obtained with `fft(...,inv=T)`.

## 3.1 Estimating $\sigma^2$

Notice that without an estimate $\hat{\boldsymbol{\eta}}$ and with only one observation for each $s(t_i), i = 1, \dots, n$ we don't have a way to construct an estimate of $\sigma^2$ based on residuals. The first difference variance estimator (Rice (1984))

$$\hat{\sigma}^2 = \{2(n-1)\}^{-1} \sum_{i=2}^{n} (y_i - y_{i-1})^2$$

provides an estimate that is not based on residuals. In practice, the procedure presented in the previous section depends heavily on this estimate. In certain circumstances, such as cases where $\sigma^2$ is small compared to $\int_0^1 \{s(t)\}^2\, dt$, $\hat{\sigma}^2$ may provide an estimate that is "too big". In this Section we propose an iterative procedure that permits us to "update" the estimate of $\sigma^2$.

Start with the first difference estimate $\hat{\sigma}^2_{(0)}$ and use it in the REACT criterion to obtain $\hat{\lambda}_{(0)}$. Now we have a fitted model and can obtain residuals which we can use to form an updated estimate of $\sigma^2$. We assume $\mathrm{E}(\hat{\boldsymbol{\eta}} - \boldsymbol{\eta}) \approx 0$ and approximate

$$\mathrm{E}|\mathbf{y} - \hat{\boldsymbol{\eta}}|^2 = \mathrm{E}[\mathbf{y}'\{\mathbf{U}\mathbf{f}(\hat{\lambda})\mathbf{U}'\}'\{\mathbf{U}\mathbf{f}(\hat{\lambda})\mathbf{U}'\}\mathbf{y}] \approx (n - \mathrm{df}_\lambda)\sigma^2.$$

We refer to $\mathrm{df}_\lambda = \mathrm{sum}\{\mathbf{f}(\hat{\lambda})^2\}$ as the *effective degrees of freedom*. We then construct a new estimate of $\sigma^2$ with

$$\hat{\sigma}^2_{(1)} = (n - \mathrm{df}_\lambda)^{-1}|\mathbf{y} - \hat{\boldsymbol{\eta}}_{(0)}|^2.$$

Continue this iterative procedure until $|\hat{\boldsymbol{\eta}}_{(k)} - \hat{\boldsymbol{\eta}}_{(k-1)}| < \delta$ with $\delta$ some small threshold. We will refer to the $\lambda$ obtained with this method as the REDACT choice, where the D stands for "dynamic". When no iterations are performed REDACT reduces to REACT.

## 3.2 Choosing $m$

The value of $m$ is usually set at 2, mainly because it is the highest value of $m$ for which the space of smoothing spline solutions is of dimension $n$ when knots are assigned to the design points $t_1, \ldots, t_n$. This makes the choice of $m = 2$ practical. However, once the problem of choosing a $\lambda$ has been reduced to (11), the shrinkage coefficients not only depend on $\lambda$ but on $m$ and we could minimize (12) over $(\lambda, m) \in [0, \infty] \times \{1, 2, \ldots\}$. In fact if we are willing to interpret fractional derivatives (McBride 1986) we can minimize (12) over

$(\lambda, m) \in [0, \infty] \times [1, \infty)$. As we will see in the following section, simulations suggest that this procedure performs well. In this paper we will refer to these criteria as REACTm and REDACTm.

# 4 Simulations

We have defined a new way of choosing the smoothness parameter for smoothing splines. In this section we compare the REACT, REDACT, REACTm, and REDACTm criteria for choosing $\lambda$ to CV, GCV, and GML using a Monte Carlo simulation. We consider 4 functions with 4 different degrees of "smoothness". The first three functions are: $s_1(t) = (1 - |2t - 1|^3)^3$, $s_2(t) = \sin(2\pi t)$, and $s_3(t) = \sum_{j=1}^{8} \rho_k \cos(2\pi t + \phi_k)$ where the $\rho_k$s and $\phi_k$s are chosen from a uniform distribution on (0,1). The fourth function is an interpolation of a local regression fit to the motorcycle data presented in Silverman (1985). In Figure 2 these functions are shown. Notice that all functions have been rescaled to have range [0,1].

For each function we create 100 simulations based on model (1) with $n = 50, 100$ and $250$ and with $\sigma = 0.025, 0.05, 0.1, 0.5$ and $1$. For each simulation we fit a periodic smoothing spline with $m = 2$ and choose the smoothing parameter with REACT, REDACT, CV (which in this case is equivalent to GCV), and GML. We also fit a periodic smoothing spline and choose both $\lambda$ and $m$ with REACTm and REDACTm. We compare the average MSE over the 100 simulations and also look at how frequently each procedure chooses a $\lambda$ producing an estimate with lower MSE than GCV, which is the default of the S-Plus function `smooth.spline()`. The results of the simulation are presented in Tables 1, 2, 3, and 4 for functions 1, 2, 3, and 4 respectively. The GML works best when the noise has large variance, i.e. $\sigma = 0.5$. However, in general the best performing criteria are REACTm and REDACTm. For function 4, the roughest function, REACT and REDACT perform better than REACTm and REDACTm except for small values of $n$ and $\sigma$ in which the GCV performs slightly better. The REACT criterion is not always improved by the iterative choice of $\hat{\sigma}^2$. As we would expect, the iterative versions seem to make an improvement when the variance is small.

Notice that for the comparison with $n = 50, \sigma = 0.05$ for function 1 we have that the CV criterion has a smaller average MSE than the REACT criterion but that the REACT criterion chooses better $\lambda$ for a larger percent of the simulations. This of course has to do with the randomness of the simulation, but also with the fact that it is quite common for a particular criterion to have a few very bad performances that bring the MSE up, but apart from these it performs well.

Finding the $\lambda$ minimizing the GML was not computationally possible in all cases. A zero in the $\lambda$ columns in the tables means no convergence was achieved. For function 3 and 4 convergence for the GML was so rare we removed it from the comparison. The code generating these simulations are available in the Software section of the author's web page: `http://www.biostat.jhsph.edu/~ririzarr`

# 5 An Example

We have activity measurements taken every 30 minutes from an AKR mouse. AKR mice are one of many animals whose activity patterns are circadian. Furthermore, our scientific intuition tells us that this pattern is probably a smooth, up-during-the-night down-during-the-day pattern (these mice are nocturnal), it thus makes sense to model the data obtained from these animals with a model like (1).

Physiologist have found that the shape of this circadian pattern can be used, for example, to assess an animals health. Therefore, finding estimates of the smooth circadian pattern is useful in practice. In Irizarry et al. (2001) the shape of the circadian pattern is used to assess homeostasis.

We observe this mouse for 47 different days, thus we can consider each of these time series as an independent identically distributed outcome of model (1). Averaging over the 47 days provides an unbiased estimate of $\boldsymbol{\eta}$ for which it is easy to obtain point-wise standard errors. Considering this average to be the evaluations of the "true" $s(t)$ at $t_1, \dots, t_n$ permits us to assess how well our smoothing splines estimate would have performed had we only had one day of data. In Figure 3 we compare the estimates obtained with the $\lambda$ chosen by CV and GML with REACT. Notice REACT chooses a smaller $\lambda$ that results in a less smooth fit that appears to be more appropriate. Noitce in particular that only with the REACT estimator do we see "two bumps". We know the second bump is "real" because we have observed the animals being active preparing there nest before sleeping.

If we obtain fits for each of the 47 days and obtain the MSE of each fit using the average of 47 day estimate as the true $s(t)$ we find that REACT has smaller MSE 29 times (62%) and has a smaller average MSE.

# 6 Extensions

In Section 3 we motivated and defined the REACT criterion for periodic smoothing splines with equally spaced knots. Extending to the general case is relatively straight-forward. Notice that in Section 2.1 we use a transformation matrix $\mathbf{U}_{DFT}$ for which we can form linear shrinkage coefficients in the context of Beran (2000) in closed form. In the general case the vector $\mathbf{f}(\lambda)$ would be the diagonal entries of $(\mathbf{I}_{n\times n} - \lambda\mathbf{\Lambda})^{-1}$. From here we can proceed to define $\mathbf{f}(\lambda)$ as in (7) but now with $f_j(\lambda) = \{1 + \lambda\Lambda_j\}^{-1}, j = 1, \dots, n$ with $\Lambda_j$ the diagonal entries of $\mathbf{\Lambda}$ and then proceed as before. The procedure is no longer as convenient from a computational stand-point because we have to compute the $\mathbf{\Lambda}$ and $\mathbf{U}$ matrices of (3) but still quite practical given that S-Plus has functions such as `qr()` and `eigen()`. However, notice that minimizing over $m$ is not as straight-forward.

In Section 3.2 we suggested that we should use the REACTm criterion to choose $\lambda$ and $m$. By doing this we are essentially changing not only the penalty multiplier but the penalty itself. This idea has recently been explored in great detail by Heckman and Ramsay (2000). The authors find that by considering different penalty criteria, estimates that perform well are obtained. The procedure described in this paper can be easily extended to be used with the procedure defined by Heckman and Ramsey. Notice in particular that the choices of $m$, shown in Tables 1–4, are between 3 and 8, which suggest that the smoothing spline methodology can be improved by changing the penalty criteria. This is in close agreement with the penalty criteria suggested by Heckman and Ramsay.

# Appendix: Theoretical Support

One can use Theorems 2.1 and 2.2 in Beran and Dümbgen (1998) to prove that minimizing the estimated risk (10) is asymptotically equivalent to minimizing the risk (9). The details of the results presented here can be found in Beran (unpublished manuscript).

If we define $\mathcal{F}$ to be the class of shrinkage coefficients $\mathbf{f}(\lambda)$ satisfying (7) it is easy to see that $\mathcal{F}$ is a closed subset of the *monotone shrinkage class* $\mathcal{F}_{MS}$ defined by Beran (2000). Furthermore, because for each element of this subset there is exactly one $\lambda$ that defines it, it is completely characterized by $\lambda \in [0, \infty]$. If we assume $\hat{\sigma}^2$ is consistent in that, for every $r > 0$ and $\sigma^2 > 0$

$$\lim_{n \to \infty} \sup_{\text{ave}(\boldsymbol{\xi}^2) \leq \sigma^2 r} \mathrm{E}|\hat{\sigma}^2 - \sigma^2| = 0$$

then one can show that for any $r > 0$ and $\sigma^2 > 0$

$$\lim_{n \to \infty} \sup_{\text{ave}(\boldsymbol{\xi}^2) \leq \sigma^2 r} \mathrm{E}| \min_{\lambda \in [0,\infty]} R(\hat{\boldsymbol{\xi}}(\lambda), \boldsymbol{\xi}, \sigma^2) - \hat{R}(\hat{\boldsymbol{\xi}}(\hat{\lambda}), \mathbf{z}, \hat{\sigma}^2)|$$

with $\hat{\lambda}$ the REACT choice. Notice as the number of observations $n$ goes to infinity we are taking a sup over all functions $s$ producing $n$-dimensional vectors $\boldsymbol{\xi} = \mathbf{U}\boldsymbol{\eta}$, with $\boldsymbol{\eta}$ the observed values of $s$ as defined in Section 2, with constrained average variability. Thus this result is not related to the prior-belief that $s$ is smooth. A result that supports the use of the $\mathbf{U}$ defined by smoothing splines together with the REACT choice of $\lambda$ when one is dealing with smooth functions follows. For every $b \in (0,1), \sigma^2 > 0$, and $r > 0$ consider the ball of smooth functions

$$B(r, b, \sigma^2) = \{\boldsymbol{\xi} : \text{ave}(\boldsymbol{\xi}^2)/\sigma^2 \leq r \text{ and } \xi_i = 0 \text{ for } i > bn\}.$$

In the case of periodic splines, this ball contains functions for which the $(1-b) \times 100\%$ highest frequency components are not present. The smaller $b$ the smoother the functions in $B(r, b, \sigma^2)$.

Given this assumption one can use Theorem 4 in Beran (2000) to find that the asymptotic minimax quadratic risk over all estimators of $\boldsymbol{\eta}$ is $\sigma^2 rb/(r+b)$ and the estimators defined by the REACT choice of $\lambda$ reach this bound:

$$\lim_{n\to\infty} \sup_{\boldsymbol{\xi} \in B(r,b,\sigma^2)} R(\hat{\boldsymbol{\xi}}(\hat{\lambda}), \boldsymbol{\xi}, \sigma^2) = \sigma^2 rb/(r+b)$$

In practice, we don't necessarily expect the smooth functions $s$ to be in any of the balls defined above. However, in the author's experience, from looking at plots of $\mathbf{z}$ for different data-sets, it seems to be a reasonable approximation. A result that somehow assumes $\xi_i \approx 0$ for $i > bn$ would be closer to what we find in practice. However, this is left as future work.

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Table 1: Comparison of the two procedures for function 1. The $\lambda$ column shows the average of the $\lambda$s chosen over the 100 simulations. The $MSE$ column shows the average of the Euclidean distances between $\hat{\boldsymbol{\eta}}$ and $\boldsymbol{\eta}$ divided by $\sigma^2$ and multiplied by 100. Finally, for each criteria except CV, the $\%$ column shows the number of times (out of the 100 simulations) that criteria beats the CV criteria in terms of Euclidean distance between $\hat{\boldsymbol{\eta}}$ and $\boldsymbol{\eta}$.

| Experiment | CV | | REACT | | | REDACT | | | GML | | | REACTm | | | | REDACTm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $n,\sigma$ | $\lambda$ | MSE | $\lambda$ | MSE | $\%$ | $\lambda$ | MSE | $\%$ | $\lambda$ | MSE | $\%$ | $\lambda$ | m | MSE | $\%$ | $\lambda$ | m | MSE | $\%$ |
| 50,0.025 | 10 | 0.74 | 19 | 0.8 | 22 | 5.4 | 0.8 | 56 | 0.13 | 1.5 | 5 | 0.12 | 5.4 | 0.74 | 47 | 0.24 | 5.7 | 0.73 | 62 |
| 50,0.05 | 22 | 0.94 | 24 | 0.92 | 46 | 14 | 1 | 59 | 4.2 | 0.99 | 41 | 0.25 | 5.2 | 0.87 | 68 | 0.54 | 5.6 | 1 | 58 |
| 50,0.1 | 55 | 1.2 | 41 | 1.2 | 63 | 32 | 1.3 | 49 | 14 | 1.2 | 50 | 14 | 4.5 | 1.2 | 59 | 2.8 | 4.8 | 1.4 | 47 |
| 50,0.5 | 460 | 2.1 | 280 | 2.1 | 49 | 270 | 2.3 | 45 | 230 | 1.9 | 58 | 1000 | 4.7 | 2.1 | 47 | 600 | 4.7 | 2.6 | 42 |
| 100,0.025 | 6.5 | 0.56 | 6.7 | 0.53 | 57 | 3.8 | 0.55 | 56 | 0 | 1.6 | 0 | 0.57 | 4.2 | 0.53 | 56 | 0.86 | 4.3 | 0.58 | 49 |
| 100,0.05 | 14 | 0.7 | 12 | 0.68 | 65 | 9.7 | 0.7 | 60 | 2.4 | 0.88 | 32 | 4.6 | 4.5 | 0.68 | 57 | 1.5 | 4.7 | 0.82 | 46 |
| 100,0.1 | 34 | 0.89 | 22 | 0.89 | 56 | 21 | 0.91 | 49 | 7.8 | 0.89 | 43 | 57 | 4 | 0.91 | 56 | 48 | 4.2 | 1.2 | 47 |
| 100,0.5 | 330 | 1.7 | 200 | 1.7 | 47 | 190 | 1.8 | 51 | 130 | 1.6 | 64 | 750 | 4.6 | 1.7 | 50 | 670 | 4.7 | 2 | 44 |
| 250,0.025 | 4 | 0.38 | 2.7 | 0.36 | 61 | 2.3 | 0.36 | 64 | 0.15 | 1.3 | 3 | 1.3 | 3.3 | 0.36 | 69 | 1.5 | 3.3 | 0.36 | 61 |
| 250,0.05 | 8.6 | 0.44 | 6 | 0.44 | 59 | 5.7 | 0.44 | 60 | 1.2 | 0.48 | 23 | 7 | 3.8 | 0.44 | 58 | 5.6 | 3.8 | 0.45 | 53 |
| 250,0.1 | 19 | 0.57 | 13 | 0.57 | 55 | 13 | 0.57 | 58 | 3.9 | 0.59 | 34 | 20 | 4.1 | 0.56 | 58 | 20 | 4.3 | 0.56 | 58 |
| 250,1 | 410 | 2 | 230 | 2.1 | 44 | 240 | 2.1 | 47 | 190 | 1.8 | 68 | 750 | 4.1 | 2.1 | 48 | 720 | 4.2 | 2.9 | 48 |

Table 2: Like table 1, but for function 2.

| Experiment | CV | | REACT | | | REDACT | | | GML | | | REACTm | | | | REDACTm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $n,\sigma$ | $\lambda$ | MSE | $\lambda$ | MSE | $\%$ | $\lambda$ | MSE | $\%$ | $\lambda$ | MSE | $\%$ | $\lambda$ | m | MSE | $\%$ | $\lambda$ | m | MSE | $\%$ |
| 50,0.025 | 29 | 0.6 | 45 | 0.63 | 33 | 20 | 0.62 | 51 | 1.7 | 0.95 | 15 | 0.13 | 7.4 | 0.42 | 94 | 0.12 | 7.5 | 0.43 | 91 |
| 50,0.05 | 49 | 0.77 | 53 | 0.75 | 60 | 35 | 0.82 | 47 | 5.9 | 0.88 | 17 | 0.35 | 6.5 | 0.59 | 90 | 0.58 | 6.7 | 0.63 | 83 |
| 50,0.1 | 110 | 1.1 | 85 | 1.1 | 52 | 74 | 1.2 | 52 | 20 | 1.1 | 44 | 43 | 6 | 0.97 | 72 | 11 | 6.1 | 1.4 | 65 |
| 50,0.5 | 1400 | 2.3 | 380 | 2.3 | 53 | 350 | 2.5 | 46 | 280 | 1.9 | 67 | 820 | 5 | 2.1 | 63 | 520 | 5.1 | 2.8 | 54 |
| 100,0.025 | 22 | 0.45 | 20 | 0.44 | 55 | 14 | 0.45 | 53 | 0 | 1.6 | 0 | 0.75 | 6.4 | 0.33 | 94 | 0.69 | 6.5 | 0.41 | 84 |
| 100,0.05 | 40 | 0.6 | 32 | 0.59 | 51 | 29 | 0.6 | 56 | 3.8 | 0.67 | 26 | 11 | 6 | 0.5 | 88 | 8.8 | 6.1 | 0.6 | 81 |
| 100,0.1 | 70 | 0.76 | 49 | 0.8 | 49 | 47 | 0.83 | 45 | 11 | 0.85 | 28 | 86 | 5.4 | 0.75 | 58 | 48 | 5.6 | 1 | 55 |
| 100,0.5 | 370 | 1.6 | 230 | 1.8 | 47 | 220 | 2 | 44 | 150 | 1.6 | 63 | 830 | 4.9 | 1.7 | 50 | 620 | 4.9 | 2.5 | 46 |
| 250,0.025 | 14 | 0.28 | 11 | 0.27 | 54 | 10 | 0.27 | 55 | 0 | 1.6 | 0 | 0.95 | 5.6 | 0.22 | 90 | 0.82 | 5.7 | 0.22 | 87 |
| 250,0.05 | 27 | 0.37 | 19 | 0.37 | 52 | 19 | 0.37 | 51 | 1.6 | 0.99 | 15 | 11 | 5.5 | 0.32 | 73 | 11 | 5.6 | 0.33 | 70 |
| 250,0.1 | 52 | 0.49 | 37 | 0.5 | 55 | 37 | 0.5 | 53 | 5.7 | 0.56 | 21 | 35 | 5.7 | 0.45 | 72 | 35 | 5.8 | 0.45 | 72 |
| 250,1 | 530 | 2 | 290 | 2.2 | 57 | 290 | 2.5 | 51 | 230 | 1.7 | 60 | 780 | 4.9 | 2.1 | 60 | 770 | 5.1 | 2.8 | 59 |

Table 3: Like table 1, but for function 3.

| experiment | cv | | REACT | | | REDACT | | | REACTm | | | | REDACTm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $n,\sigma$ | $\lambda$ | MSE | $\lambda$ | MSE | % | $\lambda$ | MSE | % | $\lambda$ | m | MSE | % | $\lambda$ | m | MSE | % |
| 50,0.025 | 0.25 | 1.1 | 0.86 | 1.6 | 1 | 0.029 | 1.5 | 17 | 3.8e-07 | 4.2 | 1.3 | 12 | 0.004 | 4.9 | 0.97 | 89 |
| 50,0.05 | 0.54 | 1.4 | 0.98 | 1.6 | 15 | 0.12 | 1.9 | 32 | 0.078 | 4.3 | 1.3 | 69 | 0.095 | 4.8 | 1.4 | 80 |
| 50,0.1 | 1.6 | 1.9 | 1.3 | 1.8 | 57 | 0.42 | 2.2 | 43 | 0.04 | 4.2 | 1.7 | 77 | 0.068 | 4.7 | 1.9 | 66 |
| 50,0.5 | 5.6e+10 | 3.2 | 1.1e+8 | 3.1 | 62 | 1.1e8 | 3.5 | 52 | 7800 | 2.8 | 3.1 | 65 | 7700 | 2.8 | 3.9 | 56 |
| 100,0.025 | 0.18 | 0.78 | 0.29 | 0.83 | 23 | 0.094 | 0.8 | 53 | 0.036 | 4 | 0.69 | 87 | 0.004 | 4.7 | 0.66 | 94 |
| 100,0.05 | 0.41 | 1 | 0.38 | 1 | 60 | 0.21 | 1 | 64 | 6.8e-07 | 4.1 | 0.91 | 97 | 0.0078 | 4.5 | 0.99 | 94 |
| 100,0.1 | 0.83 | 1.3 | 0.6 | 1.3 | 60 | 0.43 | 1.4 | 57 | 0.19 | 3.9 | 1.2 | 86 | 0.086 | 4 | 1.5 | 77 |
| 100,0.5 | 1.1e10 | 2.6 | 6.6e6 | 2.5 | 60 | 6.6e6 | 2.6 | 65 | 33000 | 2.7 | 2.5 | 58 | 33000 | 2.9 | 3.2 | 47 |
| 250,0.025 | 0.11 | 0.52 | 0.1 | 0.5 | 58 | 0.07 | 0.51 | 65 | 0.071 | 3.9 | 0.43 | 98 | 0.036 | 4 | 0.48 | 97 |
| 250,0.05 | 0.21 | 0.68 | 0.17 | 0.67 | 65 | 0.14 | 0.68 | 53 | 0.075 | 3.8 | 0.61 | 93 | 0.048 | 3.8 | 0.69 | 90 |
| 250,0.1 | 0.5 | 0.91 | 0.31 | 0.89 | 62 | 0.29 | 0.89 | 64 | 0.84 | 3.6 | 0.84 | 86 | 0.43 | 3.7 | 0.99 | 83 |
| 250,1 | 1.2e10 | 3.1 | 1.3e6 | 2.9 | 64 | 9e6 | 2.9 | 56 | 1.5e4 | 2.5 | 2.9 | 65 | 1.5e4 | 2.5 | 3.2 | 62 |

Table 4: Like table 1, but for function 4.

| experiment | cv | | REACT | | | REDACT | | | REACTm | | | | REDACTm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $n,\sigma$ | $\lambda$ | MSE | $\lambda$ | MSE | % | $\lambda$ | MSE | % | $\lambda$ | m | MSE | % | $\lambda$ | m | MSE | % |
| 50,0.025 | 0.67 | 1.1 | 2.3 | 1.3 | 3 | 0.15 | 1.3 | 36 | 0.039 | 4.6 | 1.3 | 4 | 0.52 | 3.6 | 1.2 | 33 |
| 50,0.05 | 2.1 | 1.3 | 2.7 | 1.3 | 38 | 0.64 | 1.6 | 38 | 0.12 | 4.5 | 1.3 | 44 | 0.35 | 4.2 | 1.5 | 38 |
| 50,0.1 | 5.2 | 1.6 | 4 | 1.5 | 66 | 1.9 | 2 | 48 | 0.54 | 4 | 1.5 | 75 | 0.15 | 4.2 | 2 | 49 |
| 50,0.5 | 2.7e10 | 3.1 | 6.3e7 | 2.8 | 63 | 6.3e7 | 3.1 | 59 | 2500 | 3.3 | 2.8 | 53 | 2000 | 3.7 | 3.8 | 41 |
| 100,0.025 | 0.46 | 0.77 | 0.63 | 0.8 | 27 | 0.2 | 0.76 | 66 | 0.038 | 3.7 | 0.8 | 29 | 0.15 | 3.6 | 0.89 | 57 |
| 100,0.05 | 1.2 | 0.98 | 1 | 0.95 | 57 | 0.63 | 1 | 59 | 0.21 | 3.6 | 0.96 | 43 | 1.5 | 3.3 | 1.3 | 39 |
| 100,0.1 | 3.1 | 1.2 | 2.1 | 1.2 | 57 | 1.7 | 1.2 | 56 | 4.4 | 3.7 | 1.2 | 63 | 12 | 3.7 | 1.5 | 51 |
| 100,0.5 | 2200 | 2.2 | 34 | 2 | 57 | 31 | 2 | 54 | 1000 | 3.3 | 2.1 | 37 | 890 | 3.6 | 2.8 | 34 |
| 250,0.025 | 0.21 | 0.52 | 0.16 | 0.5 | 61 | 0.11 | 0.5 | 65 | 0.38 | 3.2 | 0.5 | 67 | 0.38 | 3.3 | 0.6 | 57 |
| 250,0.05 | 0.58 | 0.65 | 0.33 | 0.63 | 63 | 0.28 | 0.64 | 54 | 2.5 | 2.9 | 0.64 | 55 | 0.76 | 2.8 | 0.8 | 48 |
| 250,0.1 | 1.6 | 0.81 | 0.94 | 0.79 | 58 | 0.87 | 0.79 | 61 | 19 | 3.1 | 0.81 | 42 | 7.8 | 3.2 | 0.97 | 40 |
| 250,1 | 1.7e9 | 2.6 | 130 | 2.6 | 53 | 140 | 2.6 | 51 | 1900 | 3 | 2.6 | 35 | 2000 | 3.1 | 3 | 34 |

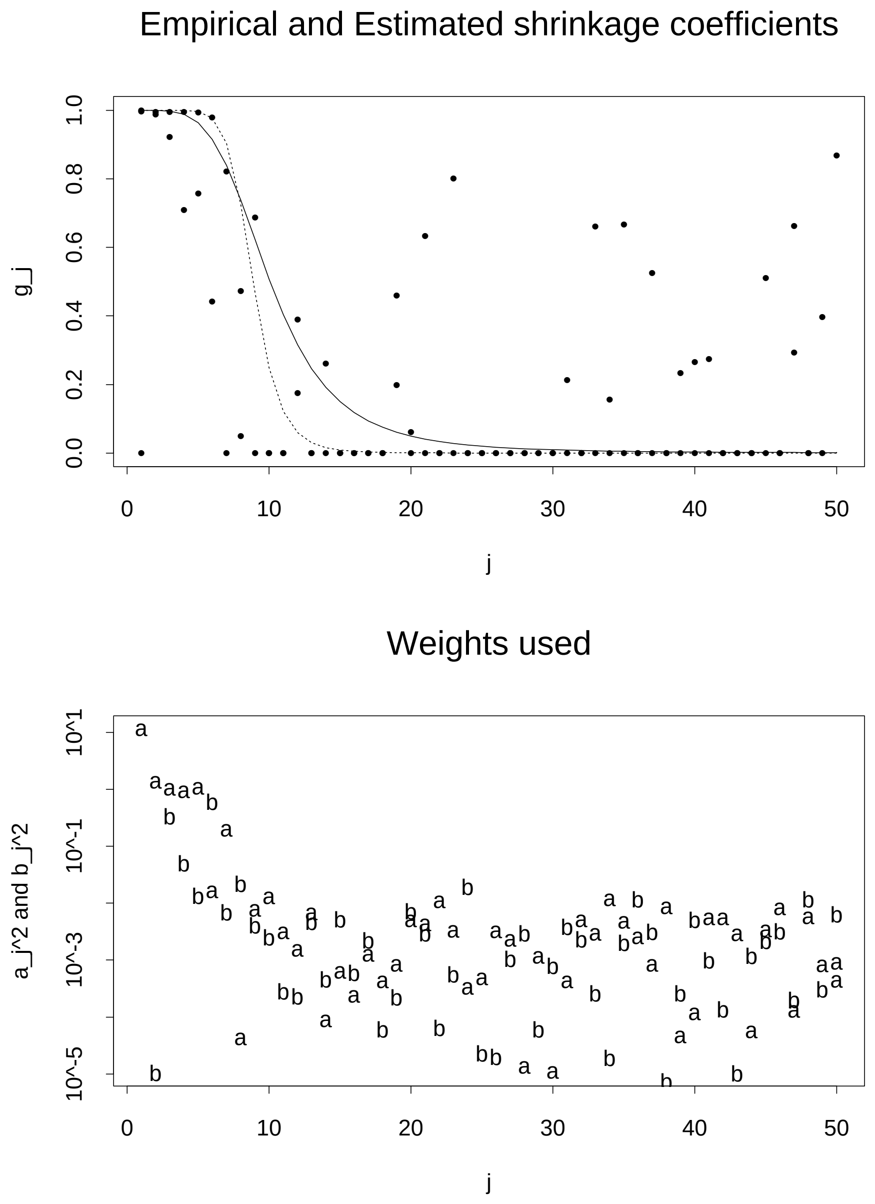


Figure 1: The first plot shows the empirical shrinkage coefficients $\hat{\mathbf{g}}$ for a Monte Carlo realization of (eq0) with $n = 100$, $\sigma = 0.05$, and $s$ is function 3. The solid line shows the fitted shrinkage coefficients using the REACT choice for $\lambda$. The dashed line shows the fitted shrinkage coefficients when both $\lambda$ and $m$ are obtained using the REACT criterion. The second plot shows the weights $\hat{a}_i$s and $\hat{b}_j$s used in the weighted least squares equation used to obtain the REACT criterion.

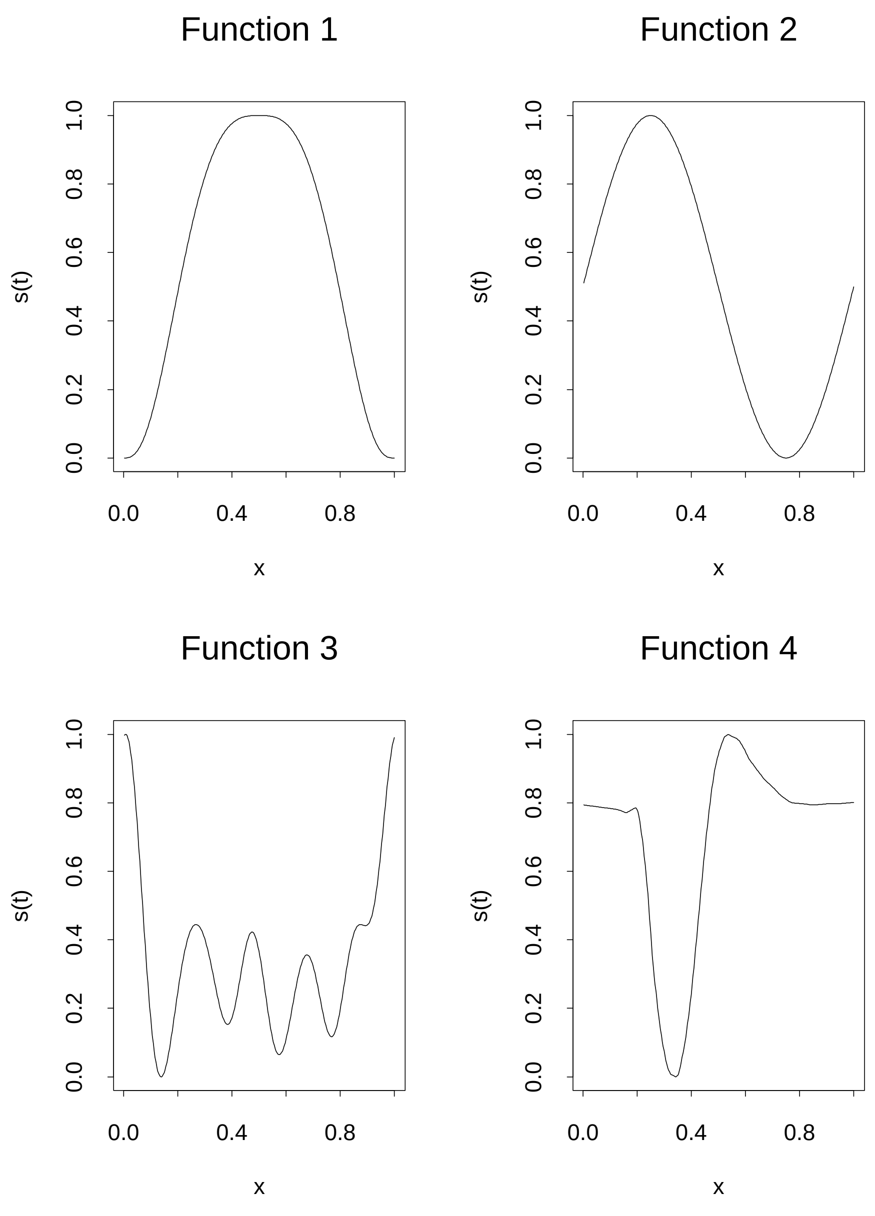


Figure 2: These are plots of the 4 functions used in the simulation.

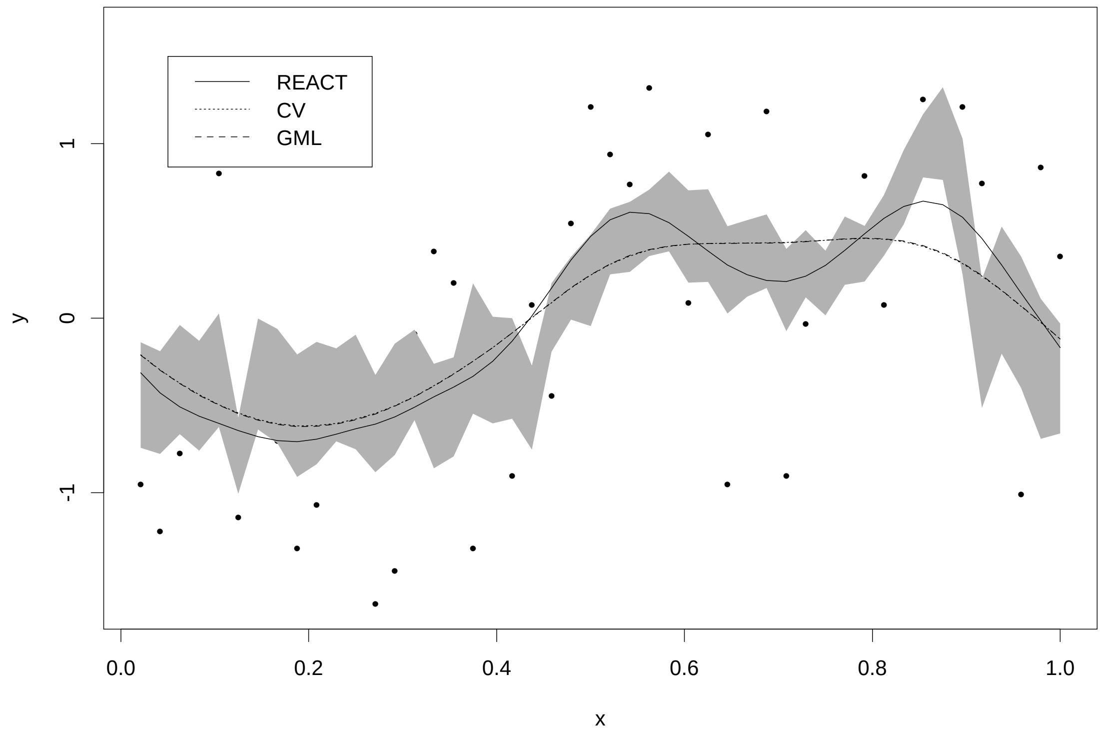


Figure 3: The points are the 48 measurements of activity taken every 30 minutes during one day for an AKR mice, The grey region denotes the unbiased estimate obtained using the mean of the 47 days we have observations from surrounded by pointwise standard errors. The solid line is the estimate obtained using the REACT criterion. The 2 dotted lines are the estimates obtained with the CV and GML criteria.