Orlicz Norms of Sequences of Random Variables

Yehoram Gordon †‡§
Technion
Department of Mathematics
Haifa 32000, Israel

gordon@techunix.technion.ac.il

Alexander Litvak †¶
Technion
Department of Mathematics
Haifa 32000, Israel
alex@math.technion.ac.il
and
University of Alberta
Edmonton, AB, T6G 2G1, Canada
alexandr@math.ualberta.ca

Carsten Schütt †
Christian Albrechts Universität
Mathematisches Seminar
24098 Kiel, Germany
schuett@math.uni-kiel.de

Elisabeth Werner ‖
Department of Mathematics
Case Western Reserve University
Cleveland, Ohio 44106, U. S. A.
and
Université de Lille 1
UFR de Mathématique
59655 Villeneuve d’Ascq, France
emw2@po.cwru.edu

*Keywords: Orlicz norms, random variables, 1991 Mathematics Subject Classification 46B07, 46B09, 46B45, 60B99, 60G50, 60G51
†Partially supported by Nato Collaborative Linkage Grant PST.CLG.977406
‡Partially supported by France-Israel Arc-en-Ciel exchange
§Partially supported by the Fund for the Promotion of Research at the Technion
¶Partially supported by a Lady Davis Fellowship
‖Partially supported by National Science Foundation Grant DMS-0072241 and by Nato Collaborative Linkage Grant PST.CLG.976356
Abstract

Let \( f_i, i = 1, \ldots, n \), be copies of a random variable \( f \) and \( N \) be an Orlicz function. We show that for every \( x \in \mathbb{R}^n \) the expectation \( E\| (x; f_i)_{i=1}^n \|_N \) is maximal (up to an absolute constant) if \( f_i, i = 1, \ldots, n \), are independent. In that case we show that the expectation \( E\| (x; f_i)_{i=1}^n \|_N \) is equivalent to \( \| x \|_M \), for some Orlicz function \( M \) depending on \( N \) and on distribution of \( f \) only. We provide applications of this result.

1 Introduction and main results

Let \( f_i, i = 1, \ldots, n \), be identically distributed random variables. We investigate here expectations

\[
E\| (x; f_i(\omega))_{i=1}^n \|_N,
\]

where \( \| \cdot \|_N \) is an Orlicz norm. We find out that these expressions are maximal (up to an absolute constant) if the random variables are in addition required to be independent.

In case the random variables are independent we get quite precise estimates for the above expectations. In particular, let \( f_1, \ldots, f_n \) be independent standard Gauß variables and let the norm on \( \mathbb{R}^n \) be defined by \( \| z \|_{k,*} = \sum_{i=1}^k z_i^* \), where \( (z_i^*) \) is the non-increasing rearrangement of the sequence \( (|z_i|) \). Then we have for all \( x \in \mathbb{R}^n \)

\[
c_1 \| x \|_M \leq E\| (x; f_i(\omega))_{i=1}^n \|_{k,*} \leq c_2 \| x \|_M,
\]

where the Orlicz function is \( M(t) = \frac{1}{k} e^{-\frac{1}{(2kt)^2}} \), \( t < 1/(2k) \), \( M(1) = 1 \). This case is of particular interest to us. In a forthcoming paper ([2]) these estimates are applied to obtain estimates for various parameters associated to the local theory of convex bodies. Let us note that in the case \( k = 1 \) the norm \( \| \cdot \|_{k,*} \) is just the \( \ell_\infty \)-norm.

Some of the methods that are used here have been developed by Kwapień and Schütt ([4], [5], [9], and [10]).

In this paper we consider random variables with finite first moments only. In the proofs of our results we assume that the random variables have continuous distributions, i.e. \( P\{ \omega | f(\omega) = t \} = 0 \) for every \( t \in \mathbb{R} \). The general case follows by approximation. We define the following parameters of the distribution. Let \( f \) be a random variable with a continuous distribution and with \( E|f| < \infty \). Let \( t_n = t_n(f) = 0 \), \( t_0 = t_0(f) = \infty \), and for \( j = 1, \ldots, n - 1 \)

\[
t_j = t_j(f) = \sup \left\{ t \mid P\{ \omega | |f(\omega)| > t \} \geq \frac{j}{n} \right\}.
\]

Since \( f \) has the continuous distribution we have for every \( j \geq 1 \)

\[
P\{ \omega | |f(\omega)| \geq t_j \} = \frac{j}{n}.
\]

We define the sets

\[
\Omega_j = \Omega_j(f) = \{ \omega | t_j \leq |f(\omega)| < t_{j-1} \}
\]
for $j = 1, \ldots, n$. Clearly, for all $j = 1, \ldots, n$

$$P(\Omega_j) = \frac{1}{n}.$$ 

Indeed

$$\Omega_j = \{ \omega \mid t_j \leq |f(\omega)| < t_{j-1} \} = \{ \omega \mid t_j \leq |f(\omega)| \} \backslash \{ \omega \mid t_{j-1} \leq |f(\omega)| \}.$$ 

Therefore we get

$$P(\Omega_j) = \frac{j}{n} - \frac{j-1}{n} = \frac{1}{n}.$$

We put for $j = 1, \ldots, n$

(3) $$y_j = y_j(f) = \int_{\Omega_j} |f(\omega)| dP(\omega).$$

We have

$$\sum_{j=1}^{n} y_j = E|f| \quad \text{and} \quad t_j \leq ny_j < t_{j-1} \quad \text{for all } j = 1, \ldots, n.$$

We recall briefly the definitions of an Orlicz function and an Orlicz norm (see e.g. [3, 6]). A convex function $M : \mathbb{R}^+ \to \mathbb{R}^+$ with $M(0) = 0$ and $M(t) > 0$ for $t \neq 0$ is called an Orlicz function. Then the Orlicz norm on $\mathbb{R}^n$ is defined by

$$\|x\|_M = \inf \left\{ \rho > 0 : \sum_{i=1}^{n} M(|x_i|/\rho) \leq 1 \right\}.$$ 

Clearly, if two Orlicz functions $M, N$ satisfy $M(t) \leq aN(bt)$ for every positive $t$ then $\|x\|_M \leq ab\|x\|_N$ for every $x \in \mathbb{R}^n$. Thus equivalent Orlicz functions generate equivalent norms. In other words to prove equivalence of $\|x\|_M$ and $\|x\|_N$ it is enough to prove equivalence of $M$ and $N$. Moreover, to define an Orlicz norm $\| \cdot \|_M$ it is enough to define an Orlicz function $M$ on $[0, T]$, where $M(T) = 1$.

Any Orlicz function $M$ can be represented as

$$M(t) = \int_0^t p(s) ds,$$

where $p(t)$ is non-decreasing function continuous from the right. If $p(t)$ satisfies

(4) $$p(0) = 0 \quad \text{and} \quad p(\infty) = \lim_{t \to \infty} p(t) = \infty$$

then we define the dual Orlicz function $M^*$ by

$$M^*(t) = \int_0^t q(s) ds,$$
where \( q(s) = \sup\{ t : p(t) \leq s \} \). Such a function \( M^* \) is also an Orlicz function and

\[
\|x\|_M \leq \|\|x\|| \leq 2\|x\|_M,
\]

where \( ||| \cdot ||| \) is the dual norm to \( \| \cdot \|_{M^*} \) (see e.g. [6]). Note that the condition (4) in fact excludes only the case \( M(t) \) is equivalent to \( t \). Note also that \( q \) satisfies condition (4) as well and that \( q = p^{-1} \) if \( p \) is an invertible function.

We shall need the following property of \( M \) and \( M^* \) (see e.g. 2.10 of [3]):

\[
(5) \quad s < M^{*-1}(s)M^{-1}(s) \leq 2s
\]

for every positive \( s \).

The aim of this paper is to prove the following theorem.

**Theorem 1** Let \( f_1, \ldots, f_n \) be independent, identically distributed random variables with \( E|f_1| < \infty \). Let \( N \) be an Orlicz function and let \( s_k, k = 1, \ldots, n^2, \) be the non-increasing rearrangement of the numbers

\[
|y_i(N^{*-1}(\frac{i}{n}) - N^{*-1}(\frac{i-1}{n}))|, \quad i, j = 1, \ldots, n,
\]

where \( y_i, i = 1, \ldots, n, \) is given by (3). Let \( M \) be an Orlicz function such that for all \( \ell = 1, \ldots, n^2 \)

\[
M^* \left( \sum_{k=1}^{\ell} s_k \right) = \frac{\ell}{n^2}.
\]

Then, for all \( x \in \mathbb{R}^n \)

\[
\frac{1}{8} \|x\|_M \leq E\| (x_i f_i(\omega))_{i=1}^n \|_N \leq \frac{8}{e-1} \|x\|_M.
\]

**Corollary 2** Let \( f_1, \ldots, f_n \) be independent, identically distributed random variables with \( E|f_1| < \infty \). Let \( M \) be an Orlicz function such that for all \( k = 1, \ldots, n \)

\[
M^* \left( \sum_{j=1}^{k} y_j \right) = \frac{k}{n}.
\]

Then, for all \( x \in \mathbb{R}^n \)

\[
c_1 \|x\|_M \leq E \max_{1 \leq i \leq n} |x_i f_i(\omega)| \leq c_2 \|x\|_M,
\]

where \( c_1, c_2 \) are absolute positive constants.

**Proof.** We choose \( p \) big enough so that the \( \ell_p \)-norm \( \| \cdot \|_p \) approximates the supremum norm \( \| \cdot \|_\infty \) well enough (\( p = n \) suffices). We consider \( N(t) = |t|^p \). This means that for all \( t > 0 \) we have

\[
N'(t) = pt^{p-1} \quad \text{and} \quad N'^{-1}(t) = \left(\frac{1}{p} t\right)^{\frac{1}{p-1}}.
\]
Therefore
\[ N^*(t) = \int_0^t N^{-1}(s) ds = \int_0^t \left(\frac{1}{p} s\right)^{\frac{1}{p-1}} ds = p^{-\frac{1}{p-1}} (1 - \frac{1}{p}) t^{1+\frac{1}{p-1}}. \]

Thus
\[ N^{*-1}(t) = p^{\frac{1}{p}} \left(\frac{p}{p-1}\right)^{\frac{p-1}{p}} t^{1-\frac{1}{p}}. \]

With this we get
\[ N^{*-1}(\frac{j}{n}) - N^{*-1}(\frac{i-1}{n}) = p^{\frac{1}{p}} \left(\frac{p}{p-1}\right)^{\frac{p-1}{p}} \left((\frac{j}{n})^{1-\frac{1}{p}} - (\frac{i-1}{n})^{1-\frac{1}{p}}\right). \]

By the Mean Value Theorem we get for \( j \geq 2 \)
\[ p^{\frac{1}{p}} (1 - \frac{1}{p})^{\frac{1}{p}} n^{-1+\frac{1}{p}} j^{\frac{1}{p}} \leq N^{*-1}(\frac{j}{n}) - N^{*-1}(\frac{i-1}{n}) \leq p^{\frac{1}{p}} (1 - \frac{1}{p})^{\frac{1}{p}} n^{-1+\frac{1}{p}} (j - 1)^{\frac{1}{p}}. \]

For sufficiently big \( p \) we have for all \( j \) with \( 1 \leq j \leq n \)
\[ \frac{1}{n} \leq N^{*-1}(\frac{j}{n}) - N^{*-1}(\frac{i-1}{n}) \leq \frac{2}{n}. \]

Now we choose \( \ell = kn \) and get
\[ \sum_{i=1}^{k} y_i \leq \sum_{j=1}^{\ell} s_j \leq 2 \sum_{i=1}^{k} y_i, \]
which implies the corollary.

**Corollary 3** Let \( f_1, \ldots, f_n \) be independent, identically distributed random variables with \( \mathbb{E} |f_i| = 1 \). Let \( k \in \mathbb{N}, 1 \leq k \leq n \), and let the norm \( \| \cdot \|_{k,*} \) on \( \mathbb{R}^n \) be given by
\[ \|x\|_{k,*} = \sum_{i=1}^{k} x^*_i, \]
where \( x^*_i, i = 1, \ldots, n, \) is the decreasing rearrangement of the numbers \( |x_i|, i = 1, \ldots, n \).

Let \( M \) be an Orlicz function such that \( M^*(1) = 1 \) and for all \( m = 1, \ldots, n - 1 \)
\[ M^* \left( \sum_{j=1}^{m} y_j \right) = \frac{m}{kn}. \]

Then, for all \( x \in \mathbb{R}^n \)
\[ c_1 \|x\|_M \leq \mathbb{E} \| (x_i f_i(\omega)) \|_{i=1}^{n} \|_{k,*} \leq c_2 \|x\|_M, \]
where \( c_1, c_2 \) are absolute positive constants.
Clearly, Corollary 3 implies Corollary 2. We state them separately here, since the proof of Corollary 3 is more involved. We could argue in the proof of this corollary in the same way as in the proof of Corollary 2. But it is less cumbersome to use the lemmas on which Theorem 1 is based.

**Proof.** Let $\epsilon > 0$ will be specified later. Consider the vector

$$z = \left(\frac{n}{k}, \ldots, \frac{n}{k}, \epsilon, \ldots, \epsilon\right),$$

where the vector contains $\left\lfloor \frac{n}{k} \right\rfloor$ coordinates that are equal to 1. (For technical reasons we require that all the coordinates of $z$ are nonzero, otherwise the function $M^*$ might not be well defined.) First we show that if $\epsilon$ is small enough then for every $x \in \mathbb{R}^n$

$$c_1 \|x\|_{k,*} \leq n^{-n+1} \sum_{1 \leq i_1, \ldots, i_n \leq n} \max_{1 \leq i \leq n} |x_i z_{i,j}| \leq c_2 \|x\|_{k,*}.$$  

To obtain this we observe first that we can choose $\epsilon$ so small that we can actually consider the vector $\bar{z} = (1, \ldots, 1, 0, \ldots, 0)/\left\lfloor \frac{n}{k} \right\rfloor$ instead. By Lemma 7 we have

$$c_n \sum_{i=1}^{n} s_i(x, \bar{z}) \leq n^{-n+1} \sum_{1 \leq i_1, \ldots, i_n \leq n} \max_{1 \leq i \leq n} |x_i \bar{z}_{i,j}| \leq \sum_{i=1}^{n} s_i(x, \bar{z}),$$

where $s_i(x, \bar{z})$ is the decreasing rearrangement of the numbers $|x_i \bar{z}_{i,j}|$, $i, j = 1, \ldots, n$. On the other hand,

$$\sum_{i=1}^{k} x_i^* \leq \sum_{i=1}^{n} s_i(x, \bar{z}) \leq \frac{n/k}{n/k} \sum_{i=1}^{k} x_i^* \leq 2 \sum_{i=1}^{k} x_i^*.$$

Let $N$ be an Orlicz function that satisfies

$$N^* \left(\sum_{i=1}^{k} z_i \right) = k/n.$$  

Lemma 5, Lemma 9, and inequalities (6) imply

$$c_3 \|x\|_N \leq \|x\|_{k,*} \leq c_4 \|x\|_N$$

for some absolute constants $c_3$, $c_4$. Clearly, $N^{*-1}(\frac{k}{n}) = N^{*-1}(\frac{k}{n}) = z_j$. Now we apply Theorem 1 to the Orlicz function $N$ and obtain the numbers $s_k$ and the function $M$ as in the statement of Theorem 1. Choosing $\epsilon$ small enough we obtain

$$s_1 = \cdots = s_{\left\lfloor \frac{n}{k} \right\rfloor} = \left(\frac{n}{k} + n - \left\lfloor \frac{n}{k} \right\rfloor \epsilon \right)^{-1} y_1,$$

$$s_{\left\lfloor \frac{n}{k} \right\rfloor + 1} = \cdots = s_{\left\lfloor \frac{n}{k} \right\rfloor + 1} = \left(\frac{n}{k} + n - \left\lfloor \frac{n}{k} \right\rfloor \epsilon \right)^{-1} y_2,$$

$$\vdots$$

$$s_{n-k+1} = \cdots = s_{n} = \left(\frac{n}{k} + n - \left\lfloor \frac{n}{k} \right\rfloor \epsilon \right)^{-1} y_n.$$
The following numbers $s_k, k = \lfloor \frac{n}{k} \rfloor + 1, \ldots, n^2$, are all smaller than $\epsilon y_1$. Since $\sum_{j=1}^n y_j = E f_i = 1$, we get $\sum_{k=1}^{n^2} s_k = 1$, which means $M^*(1) = 1$ and

$$\sum_{i=1}^{j \lfloor \frac{n}{k} \rfloor} s_i = \frac{n}{k} + (n - \frac{n}{k}) \epsilon \sum_{i=1}^j y_i.$$ 

This means that for $j = 1, \ldots, n$

$$M^* \left( \frac{n}{k} + (n - \frac{n}{k}) \epsilon \sum_{i=1}^j y_i \right) = \frac{j \lfloor \frac{n}{k} \rfloor}{n^2}.$$

Therefore there are absolute constants $c$ and $C$ such that

$$c \frac{j}{kn} \leq M^* \left( \sum_{i=1}^j y_i \right) \leq C \frac{j}{kn}.$$

Theorem 1 implies the result. \[ \square \]

**Remark.** In particular in the proof we get that for every $x \in \mathbb{R}^n$

$$n^{-n+1} \sum_{1 \leq j_1, \ldots, j_n \leq n} \max_{1 \leq i \leq n} |x_i z_{j_i}| \leq c_{n,k} \|x\|_{k,*},$$

where $c_n = 1 - (1 - 1/n)^n$ and $c_{n,k} = \frac{n}{k} / \lfloor \frac{n}{k} \rfloor \leq 2$.

**Theorem 4** Let $f_1, \ldots, f_n, g_1, \ldots, g_n$ be identically distributed random variables. Suppose that $g_1, \ldots, g_n$ are independent. Let $M$ be an Orlicz function. Then we have for all $x \in \mathbb{R}^n$

$$E \left\| (x_i f_i(\omega))_{i=1}^n \right\|_M \leq \frac{16e}{e - 1} E \left\| (x_i g_i(\omega))_{i=1}^n \right\|_M.$$

**Remark** The subspaces of $L_1$ with a symmetric basis or symmetric structure can be written as an average of Orlicz-spaces, more precisely: the norm in such a space is equivalent to an average of Orlicz-norms. Thus our theorems and corollaries extend naturally (for subspaces of $L_1$ with a symmetric basis see [1] and for the case of symmetric lattices see [7]).

## 2 Proofs of the theorems

To approximate Orlicz norms on $\mathbb{R}^n$ we will use the following norm. Given a vector $z \in \mathbb{R}^m$ with $z_1 \geq z_2 \geq \cdots \geq z_m > 0$ denote

$$\|x\|_z = \max_{\sum_{i=1}^{k_i=m} \sum_{j=1}^{k_i} z_j} \left( \sum_{j=1}^{k_i} z_j \right) |x_i|.$$
In this definition we allow some of the \( k_i \) to be 0 (setting \( \sum_{i=1}^{0} z_j = 0 \)).

The following lemma was proved by S. Kwapien and C. Schuett (Lemma 2.1 of [5]).

**Lemma 5** Let \( n, m \in \mathbb{N} \) with \( n \leq m \), and let \( y \in \mathbb{R}^m \) with \( y_1 \geq y_2 \geq \cdots \geq y_m > 0 \), and let \( M \) be an Orlicz function that satisfies for all \( k = 1, \ldots, m \)

\[
M^* \left( \sum_{i=1}^{k} y_i \right) = \frac{k}{m}.
\]

Then we have for every \( x \in \mathbb{R}^n \)

\[
\frac{1}{2} \| x \|_y \leq \| x \|_M \leq 2 \| x \|_y.
\]

**Remark.** Note that for every Orlicz function \( M \) there exists a sequence \( y_1 \geq y_2 \geq \cdots \geq y_m > 0 \) such that

\[
M^* \left( \sum_{i=1}^{k} y_i \right) = \frac{k}{m}
\]

for every \( k \leq m \).

Because of Lemma 5, to prove both our theorems it is enough to prove the following proposition.

**Proposition 6** Let \( f_1, \ldots, f_n \) be identically distributed random variables (not necessarily independent). Let \( N \) be an Orlicz function and denote

\[
z_j = N^{*-1} \left( \frac{j}{n} \right) - N^{*-1} \left( \frac{j-1}{n} \right), \quad j = 1, \ldots, n.
\]

Let \( s = (s_k)_{k \in \mathbb{R}^n} \) be the non-increasing rearrangement of the numbers \( |y_i z_j|, i, j = 1, \ldots, n \), where the numbers \( y_i, i = 1, \ldots, n \), are given by (3). Then, for all \( x \in \mathbb{R}^n \)

\[
\mathbb{E} \| (x_i f_i(\omega))_{i=1}^n \|_z \leq 2 \frac{c_n}{c_n} \| x \|_s,
\]

where \( c_n = 1 - (1 - 1/n)^n > 1 - 1/e \).

Moreover, if the random variables \( f_1, \ldots, f_n \) are independent then for all \( x \in \mathbb{R}^n \)

\[
\frac{1}{2} \| x \|_s \leq \mathbb{E} \| (x_i f_i(\omega))_{i=1}^n \|_z.
\]

To prove this proposition we need lemmas 7 – 11.

**Lemma 7** Let \( a_{i,j}, i, j = 1, \ldots, n \), be a matrix of real numbers. Let \( s(k), k = 1, \ldots, n^2 \), be the decreasing rearrangement of the numbers \( |a_{i,j}|, i, j = 1, \ldots, n \). Then

\[
\frac{c_n}{n} \sum_{k=1}^{n} s(k) \leq n^{-n} \sum_{j_1, \ldots, j_n=1}^{n} \max_{1 \leq i \leq n} |a_{i,j_i}| \leq \frac{1}{n} \sum_{k=1}^{n} s(k),
\]

where \( c_n = 1 - (1 - 1/n)^n \). Both inequalities are optimal.
Proof. Both expressions

\[ n^{-n} \sum_{j_1,\ldots,j_n=1}^{n} \max_{1 \leq i \leq n} |a_{i,j_i}| \quad \text{and} \quad \sum_{k=1}^{n} s(k) \]

are norms on the space of \( n \times n \)-matrices. We show first the right hand inequality. The extreme points of the unit ball of the norm \( \sum_{k=1}^{n} s(k) \) are – up to a permutation of the coordinates – of the form

\[ (\epsilon_1 a, \epsilon_2 b, \epsilon_3 b, \ldots, \epsilon_{n^2} b) \]

with \( a \geq b \geq 0 \), \( a + (n-1)b = 1 \), and \( \epsilon_i = \pm 1 \), \( i \leq n^2 \). This means that such a matrix has the property: The absolute values of the coordinates are \( b \) except for one coordinate which is \( a \). We get

\[ n^{-n} \sum_{j_1,\ldots,j_n=1}^{n} \max_{1 \leq i \leq n} |a_{i,j_i}| = \frac{1}{n} a + \frac{n-1}{n} b = \frac{1}{n} \]

Now we show the left hand inequality. Clearly, we may assume that at most \( n \) coordinates of the matrix are different from 0. Next we observe that we may assume that for each row in the matrix there is at most one entry that is different from 0. In fact we may assume that this is the first coordinate in the row. Now we average the nonzero entries, leaving us with the case that all nonzero coordinates are equal. In fact, we may assume that these coordinates equal 1.

Thus \( \max_{1 \leq i \leq n} |a_{i,j_i}| \) takes the value 0 or 1. In fact, it takes the value 0 exactly \( (n - 1)^n \) out of \( n^n \) times. It follows

\[ n^{-n} \sum_{j_1,\ldots,j_n=1}^{n} \max_{1 \leq i \leq n} |a_{i,j_i}| = 1 - (1 - \frac{1}{n})^n \]

which proves the lemma.

Lemma 8 Let \( a_{i,j,k} \), \( i, j, k = 1, \ldots, n \), be nonnegative real numbers. Let \( s_{\ell} \), \( \ell = 1, \ldots, n^3 \), be the decreasing rearrangement of the numbers \( a_{i,j,k} \), \( i, j, k = 1, \ldots, n \). Then

\[ \frac{1}{2n^2} \sum_{\ell=1}^{n^2} s_{\ell} \leq n^{-2n} \sum_{1 \leq j_1,\ldots,j_n \leq n} \max_{1 \leq i \leq n} a_{i,j_i,k_i} \leq \frac{1}{n^2} \sum_{\ell=1}^{n^2} s_{\ell}. \]

Proof. The right hand inequality is shown as in Lemma 7. For the left hand inequality we use here a counting argument.
Note that without loss of generality we may assume that the sequence \( \{s_k\} \) is strongly decreasing. There are exactly \( n^2 - n + 1 \) out of \( n^2 \) multiindices \((j_1, \ldots, j_n, k_1, \ldots, k_n)\) such that

\[
\max_{1 \leq i \leq n} a_{i,j_i,k_i} = s_1.
\]

Now we estimate for \( k \geq 2 \) how many multiindices there are such that

\[
\max_{1 \leq i \leq n} a_{i,j_i,k_i} = s_k.
\]

Clearly, one of the coordinates \( a_{i,j_i,k_i} \) has to equal \( s_k \), but none of these coordinates may equal \( s_j \) for \( j = 1, \ldots, k - 1 \). The second condition means that for every \( i \) (except for the row with the coordinate equal to \( s_k \)) there are \( j_i^k \) coordinates that have to be avoided and \( \sum_{i=1}^n j_i^k = k - 1 \). Let us assume that the coordinate that equals \( s_k \) is an element of the first row. This leaves us with

\[
\prod_{i=2}^n (n^2 - j_i^k)
\]

multiindices. Therefore we get

\[
n^{-2n} \sum_{1 \leq i \leq n} \max_{1 \leq j_1, \ldots, j_n \leq n} a_{i,j_i,k_i} \geq \frac{1}{n^2} \sum_{k=1}^{n^2} s_k \prod_{i=2}^n \left(1 - \frac{j_i^k}{n^2}\right)
\]

\[
\geq \frac{1}{n^2} \sum_{k=1}^{n^2} s_k \left(1 - \frac{k - 1}{n^2}\right)
\]

\[
\geq \frac{1}{n^2} \sum_{k=1}^{n^2} s_k
\]

since

\[
\sum_{k=1}^{n^2} k s_k = \sum_{j=1}^{n^2} \sum_{k=j}^{n^2} s_k = \sum_{j=1}^{n^2} \left( \sum_{k=1}^{n^2} s_k - \sum_{k=1}^{j-1} s_k \right)
\]

\[
\leq \sum_{j=1}^{n^2} \left( \sum_{k=1}^{n^2} s_k - \frac{j - 1}{n^2} \sum_{k=1}^{n^2} s_k \right) = \frac{n^2 + 1}{2} \sum_{k=1}^{n^2} s_k.
\]

That completes the proof. \( \square \)

**Lemma 9** Let \( n \in \mathbb{N} \), and let \( y \in \mathbb{R}^n \) with \( y_1 \geq y_2 \geq \cdots \geq y_n > 0 \). Then we have for \( x \in \mathbb{R}^n \)

\[
c_n \|x\|_y \leq n^{-n+1} \sum_{1 \leq i \leq n} \max_{1 \leq j_1, \ldots, j_n \leq n} |x_i y_{j_i}| \leq \|x\|_y,
\]

where \( c_n = 1 - (1 - \frac{1}{n})^n \).
Proof. We show the right hand inequality. By Lemma 7

\[ n^{-n+1} \sum_{1 \leq j_1, \ldots, j_n \leq n} \max_{1 \leq i \leq n} |x_i y_{j_i}| \leq \sum_{k=1}^{n} s_k(x, y), \]

where \( \{s_k(x, y)\}_{k \leq n^2} \) is the non-increasing rearrangement of \( \{|x_i y_j|\}_{i, j \leq n} \). Therefore there are numbers \( k_i, i = 1, \ldots, n \), with \( \sum_{i=1}^{n} k_i = n \) such that

\[ n^{-n+1} \sum_{1 \leq j_1, \ldots, j_n \leq n} \max_{1 \leq i \leq n} |x_i y_{j_i}| \leq \sum_{i=1}^{n} |x_i| \sum_{k=1}^{k_i} y_k \leq \|x\|_y. \]

Now we show the left hand inequality. By Lemma 7

\[ c_n \sum_{k=1}^{n} s_k(x, y) \leq n^{-n+1} \sum_{j_1, \ldots, j_n = 1}^{n} \max_{1 \leq i \leq n} |x_i y_{j_i}|. \]

Therefore, we have for all numbers \( k_i, i = 1, \ldots, n \), with \( \sum_{i=1}^{n} k_i = n \)

\[ c_n \sum_{i=1}^{n} |x_i| \sum_{k=1}^{k_i} y_k \leq n^{-n+1} \sum_{j_1, \ldots, j_n = 1}^{n} \max_{1 \leq i \leq n} |x_i y_{j_i}|. \]

The result follows by definition of \( \| \cdot \|_y \). \qed

Lemma 10 Let \( f_1, \ldots, f_n \) be independent, identically distributed random variables with \( \mathbb{E}|f_1| < \infty \). Let \( y_j, j = 1, \ldots, n \), be defined as in (3). Let \( \| \cdot \| \) be a 1-unconditional norm on \( \mathbb{R}^n \). Then we have for all \( x \in \mathbb{R}^n \)

\[ n^{-n+1} \sum_{j_1, \ldots, j_n = 1}^{n} \|(x_i y_{j_i})_{i=1}^{n}\| \leq \mathbb{E}\|(x_i f_i(\omega))_{i=1}^{n}\|. \]

Proof. Let \( t_j(f_i) \) and \( \Omega_j^i := \Omega_j(f_i), i, j \leq n \), be defined by (1) and (2). Since the functions \( f_i, i = 1, \ldots, n \), are identically distributed, the numbers \( t_i(f_j) \) do not depend on the functions \( f_j \). Below we will write just \( t_j \).

For \( j_1, \ldots, j_n \) with \( 1 \leq j_1, \ldots, j_n \leq n \) we put

\[ \Omega_{j_1, \ldots, j_n} = \bigcap_{i=1}^{n} \Omega_{j_i}^i. \]

Since \( f_1, \ldots, f_n \) are independent we have

\[ P(\Omega_{j_1, \ldots, j_n}) = n^{-n}. \]
For \((j_1, \ldots, j_n) \neq (i_1, \ldots, i_n)\) we have
\[
\Omega_{j_1, \ldots, j_n} \cap \Omega_{i_1, \ldots, i_n} = \emptyset.
\]
Using this and the unconditionality of the norm we obtain
\[
E\| (x_i f_i(\omega))_{i=1}^n \|^n = \sum_{j_1, \ldots, j_n = 1}^n \int_{\Omega_{j_1, \ldots, j_n}} \| (x_i f_i(\omega))_{i=1}^n \| dP(\omega)
\geq \sum_{j_1, \ldots, j_n = 1}^n \left\| \left( x_i \int_{\Omega_{j_1, \ldots, j_n}} |f_i(\omega)| dP(\omega) \right)_{i=1}^n \right\|
= n^{-n+1} \sum_{j_1, \ldots, j_n = 1}^n \| (x_i y_j)_{i=1}^n \|.
\]
For the last equality we have to show
\[
\int_{\Omega_{j_1, \ldots, j_n}} |f_i(\omega)| dP(\omega) = n^{-n+1} y_{j_i}.
\]
We check this. The functions
\[
|f_i|\chi_{\Omega_i^1}, \chi_{\Omega_i^2}, \ldots, \chi_{\Omega_i^{i-1}}, \chi_{\Omega_i^{i+1}}, \ldots, \chi_{\Omega_i^n}
\]
are independent. Therefore we get
\[
\int_{\Omega_{j_1, \ldots, j_n}} |f_i(\omega)| dP(\omega) = \int_{\Omega} |f_i(\omega)| \chi_{\Omega_i^1} \cdots \chi_{\Omega_i^n} dP(\omega)
= n^{-n+1} \int_{\Omega_{j_i}} |f_i(\omega)| dP(\omega).
\]
\[
\square
\]

**Lemma 11** Let \(f_1, \ldots, f_n\) be identically distributed random variables (not necessarily independent) with \(E|f_1| < \infty\). Let \(y_j, j = 1, \ldots, n\), be defined as in (3). Let \(z_1 \geq z_2 \geq \cdots \geq z_n \geq 0\). Let \(s_k(x, y, z), k = 1, \ldots, n^2\), be the decreasing rearrangement of the numbers \(|x_i y_j z_k|, i, j, k = 1, \ldots, n\). Then we have for all \(x \in \mathbb{R}^n\)
\[
E \max_{1 \leq i \leq n} |x_i z_{k_i} f_i(\omega)| \leq \frac{2}{n} \sum_{k=1}^{n^2} s_k(x, y, z).
\]

**Proof.** Let \(\mu\) be the normalized counting measure on \(\{k = (k_1, \ldots, k_n)|1 \leq k_1, \ldots, k_n \leq n\}\). For \(i = 1, \ldots, n\) define the functions \(\zeta_i : \{k = (k_1, \ldots, k_n)|1 \leq k_1, \ldots, k_n \leq n\} \to \mathbb{R}\), \(i = 1, \ldots, n\), by \(\zeta_i(k) = z_{k_i}\) and we put
\[
\Lambda_i = \left\{ (\omega, k) \left| |x_i \zeta_i(k) f_i(\omega)| = \max_{1 \leq \ell \leq n} |x_i \zeta_\ell(k) f_\ell(\omega)| \right. \right\}.
\]
We may assume that the sets $\Lambda_i, i = 1, \ldots, n$, are disjoint. In case they are not disjoint, we make them disjoint. Therefore

$$\sum_{i=1}^{n} P \times \mu(\Lambda_i) = 1.$$ 

We define numbers $\lambda_i$ and sets $\tilde{\Lambda}_i, i = 1, \ldots, n$, by

$$P \times \mu\{(\omega, k)||\zeta_i(k)f_i(\omega)| \geq \lambda_i\} = P \times \mu(\Lambda_i) \quad \text{and} \quad \tilde{\Lambda}_i = \{(\omega, k)||\zeta_i(k)f_i(\omega)| \geq \lambda_i\}.$$ 

The existence of these numbers $\lambda_i$ follows from the continuity of distribution of the functions $f_i$ (cf. definition of $t_j(f)$). We have

$$\sum_{i=1}^{n} P \times \mu(\tilde{\Lambda}_i) = 1$$

and

$$\tilde{\Lambda}_i = \bigcup_{\ell=1}^{n} \{k|\zeta_i(k) = z_\ell\} \times \{\omega||f_i(\omega)| \geq \frac{\lambda_i}{z_\ell}\}.$$ 

Since $\mu\{k|k_i = \ell\} = \mu\{k|\zeta_i(k) = z_\ell\} = \frac{1}{n}$ we get

$$P \times \mu(\tilde{\Lambda}_i) = \frac{1}{n} \sum_{\ell=1}^{n} P\{\omega||f_i(\omega)| \geq \frac{\lambda_i}{z_\ell}\}.$$ 

As in the previous lemma we denote

$$\Omega_j^i = \Omega_j(f_i) = \{\omega|t_j \leq f_i(\omega) < t_{j-1}\}.$$ 

For $(i, \ell)$ we choose $j_{i,\ell} = 1$ if $t_1 \leq \frac{\lambda_i}{z_\ell}$ and $j_{i,\ell}$ with

$$t_{j_{i,\ell}} \leq \frac{\lambda_i}{z_\ell} < t_{j_{i,\ell}-1}$$

otherwise. Then we have

$$\{\omega||f_i(\omega)| \geq \frac{\lambda_i}{z_\ell}\} \subseteq \{\omega||f_i(\omega)| \geq t_{j_{i,\ell}}\} = \bigcup_{i=1}^{j_{i,\ell}} \Omega_j^i$$

and

$$\{\omega||f_i(\omega)| \geq \frac{\lambda_i}{z_\ell}\} \supseteq \{\omega||f_i(\omega)| \geq t_{j_{i,\ell}-1}\} = \bigcup_{i=1}^{j_{i,\ell}-1} \Omega_j^i,$$

setting $\bigcup_{j=1}^{i} \Omega_j^i = \emptyset$. Therefore we have

$$1 = \sum_{i=1}^{n} P \times \mu(\tilde{\Lambda}_i) = \sum_{i=1}^{n} \frac{1}{n} \sum_{\ell=1}^{n} P\{\omega||f_i(\omega)| \geq \frac{\lambda_i}{z_\ell}\} \geq \sum_{i=1}^{n} \frac{1}{n} \sum_{\ell=1}^{n} P\left(\bigcup_{j=1}^{j_{i,\ell}-1} \Omega_j^i\right).$$
Thus we get
\[ n^2 \geq \sum_{i,\ell=1}^{n} (j_{i,\ell} - 1), \]
which gives us
\[ 2n^2 \geq \sum_{i,\ell=1}^{n} j_{i,\ell}. \]

By the definitions of the sets \( \Lambda_i \) and \( \tilde{\Lambda}_i \) we obtain
\[
n^{-n} \sum_{k} \mathbb{E} \max_{1 \leq i \leq n} |x_i \zeta_i(k)f_i(\omega)| = \sum_{i=1}^{n} \int_{\Lambda_i} |x_i \zeta_i(k)f_i(\omega)| dP(\omega) d\mu(k) \\
\leq \sum_{i=1}^{n} \int_{\tilde{\Lambda}_i} |x_i \zeta_i(k)f_i(\omega)| dP(\omega) d\mu(k).
\]
Since \( \tilde{\Lambda}_i \subseteq \bigcup_{\ell=1}^{n} \left( \{k | \zeta_i(k) = z_\ell\} \times \bigcup_{j=1}^{j_{i,\ell}} \Omega_{ji} \right) \),
\[
n^{-n} \sum_{k} \mathbb{E} \max_{1 \leq i \leq n} |x_i \zeta_i(k)f_i(\omega)| \leq \frac{1}{n} \sum_{i=1}^{n} \sum_{\ell=1}^{n} |x_i z_\ell| \int_{\bigcup_{j=1}^{j_{i,\ell}} \Omega_{ji}} |f_i(\omega)| dP(\omega) \\
\leq \frac{1}{n} \sum_{i=1}^{n} \sum_{\ell=1}^{n} |x_i z_\ell| \sum_{j=1}^{j_{i,\ell}} y_j.
\]
Since \( 2n^2 \geq \sum_{i,\ell=1}^{n} j_{i,\ell} \), we get
\[
n^{-n} \sum_{k} \mathbb{E} \max_{1 \leq i \leq n} |x_i \zeta_i(k)f_i(\omega)| \leq \frac{1}{n} \sum_{i=1}^{n} 2n^2 s_i(x, y, z) \leq \frac{2}{n} \sum_{i=1}^{n} n^2 s_i(x, y, z).
\]

**Proof of Proposition 6.** Let \( t_\ell, \ell = 1, \ldots, n^3 \), denote the decreasing rearrangement of the numbers
\[ |x_i y_j \left( N^{s-1}\left( \frac{k}{n} \right) - N^{s-1}\left( \frac{k-1}{n} \right) \right)|, \quad i, j, k = 1, \ldots, n. \]
Then, by definitions of the numbers \( s_i \), there are numbers \( k_i \) with \( \sum_{i=1}^{n} k_i = n^2 \) such that
\[
\sum_{\ell=1}^{n^2} t_\ell = \sum_{i=1}^{n} |x_i| \sum_{\ell=1}^{k_i} s_\ell,
\]
setting \( \sum_{\ell=1}^{0} s_\ell = 0 \). Moreover, for every numbers \( m_i \) with \( \sum_{i=1}^{n} m_i = n^2 \) we have
\[
\sum_{\ell=1}^{n^2} t_\ell \geq \sum_{i=1}^{n} |x_i| \sum_{\ell=1}^{m_i} s_\ell,
\]
\[ 13 \]
which means
\[ \sum_{\ell=1}^{n^2} t_{\ell} = \|x\|s. \]

By Lemma 9
\[ \mathbb{E}\| (x_i f_i(\omega))_{i=1}^n \|_z \leq \frac{1}{c_n} n^{-n+1} \sum_{1 \leq k_1, \ldots, k_n \leq n} \mathbb{E} \max_{1 \leq i \leq n} |x_i z_{k_i} f_i(\omega)| \]

By Lemma 11
\[ \mathbb{E}\| (x_i f_i(\omega))_{i=1}^n \|_z \leq \frac{2}{c_n} \sum_{\ell=1}^{n^2} t_{\ell} = \frac{2}{c_n} \|x\|s. \]

Now we show the “moreover” part of the Proposition. By Lemma 10
\[ \mathbb{E}\| (x_i f_i(\omega))_{i=1}^n \|_z \geq n^{-n+1} \sum_{j_1, \ldots, j_n = 1}^n \| (x_i y_{j_i})_{i=1}^n \|_z. \]

By Lemma 9
\[ \mathbb{E}\| (x_i f_i(\omega))_{i=1}^n \|_z \geq n^{-2n+2} \sum_{1 \leq j_1, \ldots, j_n \leq n} \max_{1 \leq i \leq n} |(x_i y_{j_i} z_{k_i})_{i=1}^n|. \]

By Lemma 8
\[ \mathbb{E}\| (x_i f_i(\omega))_{i=1}^n \|_z \geq \frac{1}{2} \sum_{\ell=1}^{n^2} t_{\ell} = \frac{1}{2} \|x\|s, \]

which proves the proposition. \qed

**Remark.** Using (7) and repeating the proof of Proposition 6 we can obtain estimates for the constants in Corollary 3. Namely, for every \( f_1, \ldots, f_n \) satisfying the condition of the proposition we have
\[ \mathbb{E}\| (x_i f_i(\omega))_{i=1}^n \|_{k, *} \leq \frac{2}{c_n} \|x\|s, \]

where \( s = (s_i)_{i=1}^n \) is the non-increasing rearrangement of the numbers \( |y_i z_j|, 1 \leq i, j \leq n, z = (1, \ldots, 1, 0, \ldots, 0)/[n/k] \). Moreover, if \( f_1, \ldots, f_n \) are independent then
\[ \|x\|s \leq 2c_{n,k} \mathbb{E}\| (x_i f_i(\omega))_{i=1}^n \|_{k, *}. \]

In particular, we have the variant of Theorem 4 for \( \| \cdot \|_{k, *}: \)
\[ (8) \quad \mathbb{E}\| (x_i f_i(\omega))_{i=1}^n \|_{k, *} \leq \frac{4c_{n,k}}{c_n} \mathbb{E}\| (x_i g_i(\omega))_{i=1}^n \|_{k, *}, \]

where \( f_1, \ldots, f_n \) satisfy the condition of Proposition 6, \( g_1, \ldots, g_n \) are independent copies of \( f_1 \), and \( c_{n,k} = \frac{n}{k}/[k] < 2, c_n = 1 - (1 - 1/n)^n > 1 - 1/e \). Let us note that taking
\( m = k([n/k] + 1) \) and applying the (8) for the sequences \((\tilde{x}_i f_i)_{i \leq m}, (\tilde{x}_i g_i)_{i \leq m}\), where \(\tilde{x} = (x_1, x_2, \ldots, x_n, 0, \ldots, 0)\) we obtain

\[
E\| (x_i f_i(\omega))_{i=1}^n \|_{k,*} \leq \frac{4e}{e - 1} E\| (x_i g_i(\omega))_{i=1}^n \|_{k,*},
\]

since \(c_{m,k} = 1\).

### 3 Examples

In this sections we provide a few examples. We need the following two lemmas about the normal distribution.

**Lemma 12** For all \(x\) with \(x > 0\)

\[
\frac{\sqrt{2\pi}}{(\pi - 1)x + \sqrt{x^2 + 2\pi}} e^{-\frac{1}{2}x^2} \leq \frac{\sqrt{\frac{2}{\pi}}}{x} \int_x^\infty e^{-\frac{1}{2}s^2} ds \leq \sqrt{\frac{2}{\pi}} e^{-\frac{1}{2}x^2}.
\]

The left hand inequality can be found in [8]. The right hand inequality is trivial.

**Lemma 13** Let \(f\) be a Gauß variable with distribution \(N(0,1)\). Let the numbers \(t_j, y_j\) be defined by (1) and (3). Then there are absolute positive constants \(c_1, c_2, c_3\) such that

(i) for all \(1 \leq j \leq n/e\) we have

\[
\sqrt{\frac{1}{2} \ln \frac{n}{j}} \leq t_j \leq \sqrt{2 \ln \frac{n}{j}} \quad \text{and} \quad \frac{c_1 n}{\sqrt{\ln n}} \leq \exp \left( t_j^2 / 2 \right) \leq \frac{c_2 n}{\sqrt{\ln n}},
\]

(ii) for all \(2 \leq j \leq n/e\) we have

\[
\frac{1}{n} \sqrt{\frac{1}{2} \ln \frac{n}{j}} \leq y_j \leq \frac{1}{n} \sqrt{2 \ln \frac{n}{j-1}} \quad \text{and} \quad \frac{\sqrt{\ln n}}{n} \leq y_1 \leq \frac{c_3 \sqrt{\ln n}}{n}.
\]

**Proof.** The inequalities for \(t_1\) and \(y_1\) follow by direct computation. The inequalities for the \(y_j\)'s follow from the inequalities for \(t_j\)'s, since \(t_j / n \leq y_j \leq t_{j-1} / n\) for every \(2 \leq j \leq n\). Let us prove the inequalities for \(t_j\)'s. By definition

\[
P\{\omega \| f(\omega) \| \geq t_j\} = \frac{1}{n}.
\]

This means

\[
\sqrt{\frac{2}{\pi}} \int_{t_j}^\infty e^{-\frac{1}{2}s^2} ds = \frac{1}{n}.
\]
By Lemma 12 we get

\begin{equation}
\frac{\sqrt{2\pi}}{(\pi - 1)t_j + \sqrt{t_j^2 + 2\pi}} e^{-\frac{1}{2}t_j^2} \leq \frac{j}{n} \leq \sqrt{\frac{2\pi}{\pi t_j}} e^{-\frac{1}{2}t_j^2}.
\end{equation}

First we show \( t_j \leq \sqrt{2\ln \frac{n}{j}} \). For this we observe that \( \frac{1}{2} e^{-\frac{1}{2}t^2} \) is decreasing on \((0, \infty)\).

Suppose now that for some \( j \) we have \( t_j > \sqrt{2\ln \frac{n}{j}} \). Therefore, using (10), we get

\[ \frac{j}{n} \leq \sqrt{\frac{2\pi}{\pi t_j}} e^{-\frac{1}{2}t_j^2} \leq \frac{1}{\sqrt{2\ln \frac{n}{j}}} \frac{j}{n}, \]

Thus we have

\[ \sqrt{2\ln \frac{n}{j}} \leq \sqrt{\frac{2}{\pi}}, \]

which is not true if \( e \cdot j \leq n \).

We show now that \( \sqrt{\frac{1}{2} \ln \frac{n}{j}} \leq t_j \). The function

\[ \frac{\sqrt{2\pi}}{(\pi - 1)x + \sqrt{x^2 + 2\pi}} e^{-\frac{1}{2}x^2} \]

is decreasing on \((0, \infty)\). Suppose now

\[ t_j < \sqrt{\frac{1}{2} \ln \frac{n}{j}}. \]

Then we have by (10)

\[ \frac{j}{n} \geq \frac{\sqrt{2\pi}}{(\pi - 1)t_j + \sqrt{t_j^2 + 2\pi}} e^{-\frac{1}{2}t_j^2} \geq \frac{\sqrt{2\pi}}{(\pi - 1)\sqrt{\frac{1}{2} \ln \frac{n}{j}} + \sqrt{\frac{1}{2} \ln \frac{n}{j} + 2\pi}} \left( \frac{j}{n} \right)^{\frac{1}{2}}, \]

which is false for \( j \leq n/e \). That proves the lemma. \( \square \)

**Example 14** Let \( f_1, \ldots, f_n \) be independent Gauß variables with distribution \( N(0, 1) \). Let \( M \) be the Orlicz function given by

\[ M(t) = \begin{cases} 
0 & t = 0 \\
e^{-3/(2t^2)} & t \in (0, 1) \\
e^{-3/2} (3t - 2) & t \geq 1.
\end{cases} \]

Then we have for all \( x \in \mathbb{R}^n \)

\[ c\|x\|_M \leq \mathbf{E} \max_{1 \leq i \leq n} \left| x_if_i(\omega) \right| \leq C\|x\|_M, \]

where \( c \) and \( C \) are absolute positive constants.
**Proof.** It is easy to see that there are absolute constants $c_1, c_2$ such that

$$c_1 k \sqrt{\ln(en/k)} \leq \sum_{j=1}^{k} \sqrt{\ln(n/j)} \leq c_2 k \sqrt{\ln(en/k)}$$

for every $k \leq n$. Since $\sum_{j=1}^{n} y_j = E|f_1| = \sqrt{2/\pi}$, Lemma 13 implies for every $k \leq n$

$$c_3 \frac{k \sqrt{\ln(en/k)}}{n} \leq \sum_{j=1}^{k} y_j \leq c_4 \frac{k \sqrt{\ln(en/k)}}{n},$$

where $c_3, c_4$ are absolute constants.

By the condition of the example, $M^{-1}(t) = \sqrt{-3/(2 \ln t)}$ on $(0, e^{-3/2})$. Thus $M^{-1}(t) \approx \sqrt{3/(2 \ln(e/t))}$ on $(0, 1)$. By (5) we observe

$$t \sqrt{2 \ln(e/t)/\sqrt{3}} \leq M^{-1}(t) \leq 2t \sqrt{2 \ln(e/t)/\sqrt{3}}.$$  

Taking $t = k/n$ and using (11) we get for every $k \leq n$

$$c_5 \sum_{j=1}^{k} y_j \leq M^{-1}(k/n) \leq c_6 \sum_{j=1}^{k} y_j,$$

where $c_5, c_6$ are absolute constants. Applying Corollary 2 we obtain the result. \hfill \Box

The next example is proved in the same way as the previous one, we just use Corollary 3 instead of Corollary 2 at the end.

**Example 15** Let $g_i, i = 1, \ldots, n$, be independent Gauß variables with distribution $N(0, 1)$, $k \leq n$, and $\|x\| = \sum_{i=1}^{k} x_i^*$. Let

$$M(t) = \begin{cases} 0 & t = 0 \\ \frac{1}{k} e^{-3/(2t^2)} & t \in (0, 1/k) \\ e^{-3/2} (3t - 2/k) & t \geq 1/k. \end{cases}$$

Then for all $\lambda \in \mathbb{R}^n$ we have

$$c_1 \|\lambda\|_M \leq E\| (\lambda_i g_i(\omega))_{i=1}^{n} \| \leq c_2 \|\lambda\|_M,$$

where $c_1$ and $c_2$ are positive absolute constants.

The following example deals with the moments of Gauß variables.
Example 16 Let $0 < q \leq \ln n$, $a_q = \max\{1, q\}$, $g_i$, $i = 1, \ldots, n$, be independent Gauß variables with distribution $N(0, 1)$, and $f_i = |g_i|^q$, $i = 1, \ldots, n$. Let

$$M(t) = \begin{cases} 0 & t = 0 \\ \frac{1}{k} \exp\left(-a_q/ (kt)^{2/q}\right) & t \in (0, t_0) \\ at - b & t \geq t_0, \end{cases}$$

where

$$t_0 = \frac{1}{k} \left(\frac{2a_q}{q + 2}\right)^{q/2}, \quad a = \frac{q + 2}{eqk} e^{-q/2}, \quad b = \frac{2}{eqk} e^{-q/2}.$$ 

Then for all $\lambda \in \mathbb{R}^n$ we have

$$cq (ca_q)^{q/2} \|\lambda\|_M \leq E \|(\lambda_i f_i(\omega))_{i=1}^n\| \leq C (Ca_q)^{q/2} \|\lambda\|_M,$$

where $0 < c < 1 < C$ are absolute constants and $\|x\| = \sum_{i=1}^k x_i^*$. This example is proved in the same way as the previous two examples. We use that

$$k \left(\sqrt{\ln(n/k)}\right)^{q/2} \leq \sum_{j=1}^k \left(\sqrt{\ln(n/j)}\right)^{q/2} \leq 2k \left(\sqrt{\ln(n/k)}\right)^{q/2}$$

for every $k \leq n/e^q$ and that

$$ca_q \leq (E |g(\omega)|^q)^{2/q} \leq Ca_q$$

for some absolute positive constants $c, C$.

Finally we apply our theorem to the $p$-stable random variables. Let us recall that a random variable $f$ is called $p$-stable, $p \in (0, 2]$, if the Fourier transform of $f$ satisfies

$$E \exp(-itf) = \exp(-c|t|^p)$$

for some positive constant $c$ (in the case $p = 2$ we obtain the Gauß variable).

Example 17 Let $p \in (1, 2)$. Let $f_1, \ldots, f_n$ be $p$-stable, independent, random variables with $E|f_i| = 1$. Let $k \leq n$ and $\|x\| = \sum_{i=1}^k x_i^*$. Let

$$M(t) = \begin{cases} \frac{1}{k} (kt)^p & t \in [0, 1/k] \\ pt + (p - 1)/k & t > 1/k. \end{cases}$$

Then for all $x \in \mathbb{R}^n$

$$c_p \|x\|_M \leq E \|(\lambda_i f_i(\omega))_{i=1}^n\| \leq C_p \|x\|_M,$$

where $c_p, C_p$ are positive constants depending on $p$ only.

In particular,

$$c_p \|x\|_p \leq E \max_{1 \leq i \leq n} |x_i f_i(\omega)| \leq C_p \|x\|_p,$$

where $\|\cdot\|_p$ denotes the standard $\ell_p$-norm.
Proof. There are positive constants $c_1$ and $c_2$ depending on $p$ only such that for all $t > 1$

$$c_1 t^{-p} \leq P\{\omega \mid |f(\omega)| \geq t\} \leq c_2 t^{-p}.$$

Thus

$$\left(\frac{c_1 n}{j}\right)^{1/p} \leq t_j \leq \left(\frac{c_2 n}{j}\right)^{1/p}.$$

Repeating the proof of Example 14 we obtain the desired result. \qed

References


