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Selection indices for quality evaluation in wheat breeding

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Summary. From multilocation trials involving 125 cultivars of wheat of mainly French and European origin four tests – protein content, Pelshenke, modified Zeleny and the mixograph – were used to establish six selection indices. Three of these indices – IW_1, IW_2 and IW_3 – were calculated in order to evaluate the genetic potentiality of the lines for dough strength as given by the Chopin alveograph. The indices IV_1, IV_2 and IV_3 were established to evaluate loaf volume as measured by the French bread-making standard. A quality index IQ was calculated from the allelic effects of the high-molecular-weight (HMW) subunits of glutenin from 195 cultivars assessed by the Chopin alveograph and the Pelshenke test. Comparison of the relative efficiency of each of the six indices to the individual tests revealed the superiority of the indices over one or several technological parameters. The six selection indices and the quality index were compared using 30 very diverse F_4 lines. Their ability to retain the good quality lines is discussed in particular.

Key words: Bread wheat – Technological quality – Loaf volume – Gluten strength – Heritability

Introduction

Breeders use various tests to evaluate wheat quality. These tests are based on the end-use quality objective of the breeding programmes, but there are also one or several indirect technological tests commonly used in a particular country and they must be feasible in the F_3, F_4 or F_5 generations. In addition to the analysis of the allelic composition of the high-molecular-weight subunits of glutenins (HMW-GS) (Payne et al. 1981) and of gliadins (Sozinov and Poperelya 1980) which can be carried out from single kernels, or half grains (Bietz et al. 1975), breeders may have many other technological tests at their disposal. Some tests have been found to be more useful than others for predicting the quality of North American wheats (Baker et al. 1971; Fowler and de la Roche 1975). With respect to European bread wheats, Branlard et al. (1991) compared 17 technological tests for their ability to be both highly heritable and correlated to quality. Some technological parameters, for example, modified Zeleny, Pelshenke test and mixograph criteria, were more suitable for predicting gluten strength or loaf volume than others. As wheat quality is the result of many components, each having different technological properties, which cannot be evaluated by only one indirect test, it appears that a very judicious combination of a few test parameters is necessary for improving the efficiency of wheat quality breeding. Some studies have formed quality indices by combining several technological parameters (Cox et al. 1989). Surprisingly, no selection index has been established for wheat quality as has been for many other agronomic characteristics of plants. The theory of genetic indices first developed by Smith (1936) on wheat was used with success for improving the genetic value of different traits in many crops, such as grain yield in maize (Robinson et al. 1951) grain and straw yield in oats (Eagles and Frey 1974) or yield and protein content in maize (Motto and Perenzin 1982; see Baker 1986 for review).

In the study presented here several indices will be established, six of which were calculated from a limited number of technological tests, each using a small amount of grain, and another from the allelic composition of the allelic composition of the HMW-GS. Their relative efficiency for improving the genotypic value of strength and loaf volume will be calculated and particularly discussed with particular reference to use F_4 offspring.

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Material and methods

The six technological indices consisted of IW_1, IW_2 and IW_3, established for improving the genotypic values of strength as evaluated by the Chopin alveograph, and IV_1, IV_2 and IV_3 for bread loaf volume.

Plant material

The six indices IW_i and IV_i were established from a total of 125 bread wheat cultivars of European origin and experimentally evaluated for 3 years (1985–1987) in six, seven and five locations, respectively, in France. These multilocation trials enabled us to compare 46 technological parameters (Branlard et al. 1991). Seventy other cultivars of very diverse genetic origins and range of quality were grown each year by the INRA wheat laboratory of Clermont-Ferrand. These seventy cultivars were used to relate gliadin and HMW-GS polymorphism to technological quality (Branlard and Dardevet 1985a, b) and were added to the previous ones also grown at Clermont-Ferrand. The means of the technological values of these 195 cultivars were used to establish the quality index IQ from their allelic HMW-GS composition.

The relative efficiency and the correlations between the indices IW_i, IV_i and IQ were computed from the 125 cultivars. The indices were compared using 30 F_4 lines derived from offspring from several complex crossings including 8 diverse bread wheat cultivars as different combinations between 37 parents. This population was selected during a 3-year breeding programme from 1987 to 1989. In the second year, plants were selected for resistance to disease and for quality using IQ. In the third year these 30 lines were used as experimental material for agronomic purposes at seven locations, and their technological qualities were evaluated from only one location.

Technological tests

From the 17 technological tests previously compared, the following were retained to build the indices of technology IW_i and IV_i: protein content (Pro), Pelshenke (Pel), modified Zeleny (Zym) and mixograph (Mixo).

The protein content was estimated on wholemeal flour by Near Infrared Reflectance (NIR). The modification of the Zeleny consisted in performing the test from a 70% instead a 20% extraction rate flour. From the 10 g mixograph, seven parameters were obtained: time taken to reach the maximum consistency of the curve (MTM), height and thickness, respectively, of the curve at the maximum (MHM and MTH). Height and thickness, respectively, of the curve after 7 min of mixing (MH7 and MT7), the product (MTM × MHM) and the sum of the six previously defined traits (MIN).

The criteria for which the indices were developed are the strength W of the Chopin alveograph and the bread loaf volume LV as given by the French standard breadmaking procedure (AFNOR V-03-713).

Indices from technological traits

The three strength indices, IW_1, IW_2 and IW_3, and the three loaf volume indices, IV_1, IV_2 and IV_3, were calculated by combining two or three of the following tests: Pro, Pel, Zym and Mixo. The mixograph test had seven parameters, consequently the maximum number of parameters used as explanatory variates xj of the strength and loaf volume was ten. The initial variates xj were standardized $x'j = (xj - mj)/\sigma j$ (where mj and σj are the mean and standard deviation of xj respectively), before calculating the multiple regression for predicting the strength W or the loaf volume LV. IW_1 and IV_1 were calculated as functions of three tests: Pro, Pel and Zym. IW_2 and IV_2 were calculated from Pro, Pel and Mixo, whereas IW_3 and IV_3 used only Pro and Mixo. The optimum number p of explanatory variates x'j introduced in the multiple regression was obtained as previously described (Branlard and Dardevet 1985a).

The general formula of indices IW_i and IV_i is written as follows

$$IV_i \text{ or } IW_i = K \sum_{j=1}^{p} c_j \beta_j h_j^2 X_j \qquad (1)$$

where h_j^2 is the general heritability calculated for each parameter x_j, as described by Branlard et al. (1991), β_j is the partial regression coefficient of the step-wise multiple regression calculated to predict W or LV from the variates x'_j, $c_j = 1/xm_j$ where xm_j is the maximum value of x_j, and K is a coefficient applied to the sum in order to obtain an index value near 100 when all x_j values are equal to their maximum xm_j.

The h_j^2, β_j, xm_j coefficients are given in Table 1. As the product $Kc_j \beta_j h_j^2$ is constant, let be $a_j = Kc_j \beta_j h_j^2$ for a given j; then the index formula (1) can be written:

$$IW_i = \sum_{j=1}^{p} a_j x_j$$

Table 1. Coefficients used in calculating the selection indices: h^2, general heritability; W_i and V_i, β_j coefficients obtained from the multiple regression to explain dough strength W and loaf volume LV, respectively

Parameter	Abbreviation	Units	Maximum	H^2	W1	W2	W3	V1	V2	V3
Protein	Pro	%db	18	0.247	0.175	0.192	0.255	−0.159	−0.123	0.091
Pelshenke	Pel	min	305	0.633	0.337	0.299		0.095	0.145	
Zeleny modified	Zym	ml	59	0.632	0.526			0.652		
Mixographe time at maximum	MTM	min	5.7	0.472		−0.104				
Height at maximum	MHM	cm	9.4	0.437			−0.250		1.692	−1.574
Thickness at maximum	MTH	cm	5.6	0.403						
Height at 7 min	MH7	cm	7.9	0.546		0.365	0.728		−2.241	2.090
Thickness at 7 min	MT7	cm	3.2	0.565		0.333	0.316		0.193	−0.233
MTM × MHM	MTM × MHM	–	36.0	0.557						
Index mixo	MIN	–	47.5	0.618						
R^2					0.75	0.81	0.78	0.43	0.60	0.60
$n = 125$										

Quality index IQ from HMW-GS

The quality indice IQ was calculated as the sum of the coefficients attributed to the HMW-GS alleles present in a given genotype. The coefficient attributed to each allele was globally proportional to the allelic effect observed for the following parameters: strength, tenacity, swelling given by the alveograph and Pelshenke. For a quality parameter k the effects were calculated for each locus and expressed in percent of the total variation Δxp observed amongst the three loci *Glu-A1, Glu-B1* and *Glu-D1*. The effect X_{kij} of the allele i from the locus j was obtained as follows: $X_{kij} = (x_{kij} - x_{krj}) \times 100/\Delta x k$; where x_{kij} is the mean value of the parameter k calculated from the varieties having the allele i at the locus j; for example, mean of the swelling of the wheats having the band 2* at *Glu-A1*.

x_{krj} is the mean value of the parameter k calculated from the varieties having the allele inducing a low quality. For a given locus j the same allele r (named here in the reference allele) was used for the four quality parameters. This reference allele was *Glu-A1c* (null allele), *Glu-B1d* (bands 6–8) and *Glu-D1a* (bands 2–12) according to the Payne and Lawrence (1983) nomenclature.

Δ_{xk} was the difference between the maximal and minimal means. The mean effect $\bar{X}_{.ij}$ was calculated as the mean of the four effects X_{kij}. The coefficient of quality Y_{ij} attributed to the allele i from the locus j was expressed as $Y_{ij} = b\bar{X}_{.ij} + aj$ where b is a coefficient and aj is a constant corresponding to the quality value attributed to the reference allele. For *Glu-A1c* (null allele) $a_1 = 0$ and for *Glu-B1d* and *Glu-D1a*, $a_2 = 2$ and $a_3 = 7$, respectively. Finally, the indice IQ is written as the sum of the three Y_{ij} coefficients:

$$IQ = \sum_{j=1}^{3} Y_{ij}$$

Comparison of the indices

The values of the indices IW_i, IV_i and IQ calculated for the 125 cultivars allowed us to compare them by two approaches. Firstly, linear correlations were calculated for each pair of indices. Secondly, the indices were compared to the technological tests by computing their relative efficiency RI/Rt (Baker 1986); RI was the expected response to selection based on index I, and Rt the expected response to selection based on the test t alone, from which the index I was built. On the assumption that the two types of selection (with the index or with test t alone) used the same selection intensity it has been demonstrated that the relative efficiency can be calculated as follows:

$$\frac{RI}{Rt} = \frac{r(Gt, I)}{ht} \quad \text{(Baker 1986)}$$

where r(Gt, I) is the correlation between the genotypic values Gt of the cultivars evaluated by the test t and the values of the indice I. The divider ht is the square root of the heritability h^2 of test t.

Criteria of selection

Thirty F_4 lines were observed using either the individual parameters or each of the indices IW_i, IV_i or IQ. The lines having a value higher than M + SE were considered to be selected. M and SE are the mean and standard error of the 30 lines, respectively.

Results

Indices from technological traits

The coefficients Xmj, β_j and h_j^2 used to build the indices are shown in Table 1. The maximal value of each technological parameter was not always from the same cultivars. As expected, the heritability of Pro was low; those of Pel, Zym and Min were higher and similar to one another. Multiple regression gave a higher R^2 coefficient for the prediction of the W value of dough than for bread loaf volume LV. The lowest R^2 coefficient of prediction of loaf volume was obtained for V_1, i.e. when the three tests Pro, Pel and Zym were combined.

Some parameters of the mixograph permitted a significant increase in the prediction coefficient for loaf volume. The use of the mixograph, together with the tests Pro and Pel gave a high coefficient of prediction for strength ($R^2 = 0.81$; $n = 125$). The combinations of mixograph parameters were not the same for the prediction of W (Table 1), but parameters MH7 and MT7 were regularly retained by the step-wise regression procedure in the prediction of W and LV.

The six selection indices established from these different coefficients are presented in Table 2. For these indices

Table 2. Indices of selection for improving the genetic value of dough strength (IW_1, IW_2, IW_3) and loaf volume (IV_1, IV_2, IV_3). The units and abbreviations of the parameters are given in Table 1

$IW_1 = 0.05\,Pro + 0.25\,Pel + 0.39\,Zym$
$IW_2 = 0.07\,Pro + 0.31\,Pel - 0.08\,MTM + 0.33\,MH7 + 0.31\,MT7$
$IW_3 = 1.65\,Pro - 2.86\,MHM + 10.41\,MH7 + 4.67\,MT7$
$IV_1 = -0.09\,Pro + 0.14\,Pel + 0.98\,Zym$
$IV_2 = -0.12\,Pro + 0.36\,Pel + 2.94\,MHM - 4.87\,MH7 + 0.43\,MT7$
$IV_3 = 0.88\,Pro - 27.15\,MHM + 45.05\,MH7 - 5.19\,MT7$

Table 3. Means and standard deviations of the selection indices value observed for five wheats, ranked from the very good (Magdalena) to the very bad (Clement), over 3 years in France

	IW_1	IW_2	IW_3	IV_1	IV_2	IV_3
Magdalena	62.6 ± 3.2	60.0 ± 5.3	76.0 ± 7.0	68.0 ± 2.6	55.0 ± 6.0	92.7 ± 6.5
Hardi	37.3 ± 3.2	29.0 ± 5.0	70.0 ± 5.5	50.3 ± 3.8	19.7 ± 5.5	92.3 ± 5.8
Capitole	41.3 ± 3.0	36.6 ± 3.2	63.6 ± 4.6	47.7 ± 2.5	30.0 ± 4.3	82.3 ± 5.1
Talent	20.6 ± 1.1	15.0 ± 1.0	61.3 ± 3.0	30.7 ± 2.0	5.3 ± 0.5	77.0 ± 2.0
Clement	13.0 ± 1.0	8.0 ± 0.2	47.6 ± 2.0	20.0 ± 2.0	1.7 ± 0.29	50.0 ± 1.7

the negative signs correspond to the β_j signs and do not mean an unfavourable effect on quality for the parameters. As the variates introduced are the true parameters without any transformation, the use of these indices is very simple. For five different wheats ranked from very poor quality (Clement) to very strong gluten (Magdalena) the magnitudes of the values for the six selection indices were different (Table 3). The magnitude of the index value range was higher when the indices were constructed from tests Pro, Pel and Mixo (e.g. for IW_2 and IV_2) than they were for the other combinations. IW_3 and IV_3 had higher values with a lower range between the bad and the good quality wheats than the other indices. For a given variety, the higher the index values, the higher their variations from year to year.

The efficiency of the indices were calculated relative to the parameters used. This relative efficiency corresponds to the comparison between the expected response to selection based on the index and the direct response when only one parameter is used. For each of the six indices, at least one parameter was found to be advantageously introduced as their expected response was superior when combined in an index to the response if it would have been used for a direct selection (Table 4). Selection based on IW_1 or IW_2 would be expected to result in a 24% or 25% greater increase in the mean genotypic value of the strength than would direct selection for strength using the Pelshenke test alone at the same selection intensity. Selection based on the index $IW_3 = 1.65$ Pro $- 2.86$ MHM $+ 10.41$ MH7 $+ 4.67$ MT7 would be expected to give a mean genotypic strength value 3–29% greater than would result from the direct use of the individual parameters. As the protein content is partly related to strength and to loaf volume and its coefficient attributed in the indice is generally low, the expected response of this parameter seems to be better when used alone. Nevertheless, the introduction of protein content with some mixograph parameters in the indices led to a better prediction of the genotypic values of the criteria W or LV to be improved.

Table 4. Relative efficiency RI/Rt values obtained when the expected response RI to selection using the index (IW_i or IV_i) is compared to the direct selection Rt based on one of the parameters introduced in the index

	IW_1	IW_2	IW_3	IV_1	IV_2	IV_3
Pro	61.3	54.3	103.7	79.9	51.5	51.0
Pel	124.7	125.7	–	116.6	125.5	–
Zym	93.3	–	–	111.8	–	–
MTM	–	88.9	–	–	–	–
MHM	–	–	118.1	–	51.5	78.2
MH7	–	81.8	129.8	–	76.0	112.6
MT7	–	90.6	106.4	–	86.6	103.5
W	92.9	87.8	106.0	–	–	–
LV	–	–	–	82.5	60.5	104.0

For abbreviations, see Table 1

Quality index from HMW-GS

From the 195 wheat cultivars the mean value of the genotypes having the same allele was calculated for each of the three alveograph parameters (strength, tenacity, swelling) and for the Pelshenke test. The comparison of these means was carried out for the main alleles at the loci *Glu-A1*, *Glu-B1* and *Glu-D1* (Table 5). For each parameter the effect x_{kij} of the alleles was calculated and their means $\bar{X}_{.ij}$ are presented. The coefficients Y_{ij} pro-

Table 5. Comparison of the means calculated on four quality parameters for the different HMW-GS alleles encountered on the 195 cultivars. Means with the same letter are not significantly different at $P = 0.95$

	Glu-A1			*Glu-B1*							*Glu-D1*			
Tenacity	2*	1	Null	17–18	7–9	7–8	6–8	13–16	7	21	5–10	3–12	4–12	2–12
(mm H_2O)	75	69	64	77	71	70	68.5	66	65	53.4	74	68	64	63
	a	b	b	a	b	b	b	bc	c	d	a	b	bc	c
Swelling	1	2*	Null	13–16	7–8	7	7–9	21	17–18	6–8	4–12	3–12	2–12	5–10
(cm^3)	21.5	21.4	20.1	20.9	20.7	20.7	20.6	20.2	19.3	19.1	20.9	20.8	20.8	20.6
	a	a	b	a	a	a	a	b	c	c	a	a	a	a
Strength	2*	1	Null	13–16	17–18	7–9	7–8	7	6–8	21	5–10	3–12	2–12	4–12
(10^{-4} J)	210	167	163	240	179	170	165	155	144	127	197	160	152	150
	a	b	b	a	b	bc	bc	bcd	cd	d	a	b	b	b
Pelshenke	2*	1	Null	13–16	21	17–18	7–9	7–8	6–8	7	5–10	2–12	3–12	4–12
(min)	145	111	100	135	129	116	110	104	90	72	144	82	70	67
	a	b	b	a	b	bc	bcd	bcd	cd	d	a	b	b	b
HMW-GS Effect	2*	1	Null	13–16	7–9	17–18	7–8	7	21	6–8	5–10	3–12	2–12	4–12
(%) $\bar{X}_{.ij}$	48.7	24.0	–	49.6	29.8	26.3	26.8	9.5	4.2	–	38.0	3.1	–	−3.0

portional to the allelic effects are shown in Table 6. They allowed us to calculate the index IQ of any genotype having 3 of the 16 alleles. For example, a genotype having the following HMW subunits of glutenins 1–2–7–8–12 would have an index IQ=40.

The index IQ is similar to the gluten score (GS) proposed by Payne et al. (1987) from several sets of offsprings and varieties assessed both by SDS-Page and by the SDS sedimentation test. Coefficients were established for the gluten score from the 14 alleles (i.e. 3 of *Glu-A1*, 7 of *Glu-B1* and 4 of *Glu-D1*), and 84 genotypes differing by their HMW allelic combination could be created. A highly significant correlation ($r=0.881$, $n=84$) was found between IQ and GS. The index IQ calculated from the three parameters of rheology (strength, tenacity and swelling) and the Pelshenke test was compared to both the six selection indices and to the technological test.

Table 6. Value of coefficient Y_{ij} attributed to 16 alleles of the HMW-GS used in the quality index IQ

Locus	Alleles	HMW-GS	Quality coefficient
Glu-A1	a	1*	15
	b	2*	30
	c	Null	0
Glu-B1	a	7	8
	b	7–8	18
	c	7–9	20
	d	6–8	2
	e	20	2
	f	13–16	32
	g	13–19	–
	h	14–15	–
	i	17–18	18
	j	21	5
Glu-D1	a	2–12	7
	b	3–12	9
	c	4–12	5
	d	5–10	30
	e	2–11	7

Comparison of the indices

The indices were applied to F_4 offspring of 30 lines displaying a wide variation for their technological values (Table 7). The correlations calculated from the phenotypic values showed strong relationships between the four indices IW_1, IW_2, IV_1 and IV_2. The index IQ was not so well related to the technological indices and was not significantly correlated to IW_3. The correlations were even lower when GS was used (data not shown). The potentialities of quality from the index IQ do not correspond to the entire variability of the quality estimated by the indices IW_i or IV_i.

Complementary results arose when we analysed the number of common lines selected both by direct selection using one parameter and by the technological indices:

1) when grain protein content was used alone for direct breeding, no more than 60% of the lines selected by the indices were retained (Table 8);

2) all lines selected by the indices which included the Pelshenke test were also retained when this test was used alone;

3) the mixograph parameters should have selected no more than 80% of the lines obtained from the indices;

4) the index IQ globally selected 50% of the total lines retained by the indices.

The values of the technological parameters were normally distributed, except for the Pelshenke test, which revealed more low quality lines than the other tests. Con-

Table 7. Statistical values of the technological parameters used to assess the quality of the 30 F_4 lines and to calculate the indices and linear correlations between the seven indices ($n=30$)

	Pro	Pel	Zym	MTM	MHM	MH7	MT7	MIN
Minima	12.95	18	25	1	6	5.5	1	19.3
Maxima	16.85	200	53	4.3	9.4	7.8	1.9	44.0
Mean (m)	14.54	69.9	39.1	2.3	7.7	6.6	1.3	29.2
m + SE	14.71	78.2	40.3	2.4	7.9	6.7	1.3	30.2

	IW_1	IW_2	IW_3	IV_1	IV_2	IV_3	IQ
IW_1	1.000						
IW_2	0.993**	1.000					
IW_3	0.739**	0.720**	1.000				
IV_1	0.972**	0.936**	0.757**	1.000			
IV_2	0.992**	0.998**	0.698**	0.937**	1.000		
IV_3	0.701**	0.728**	0.618**	0.622**	0.686**	1.000	
IQ	0.571**	0.559**	0.329	0.567**	0.557**	0.442*	1.000

*, ** Significantly correlated at 5% and 1%, respectively

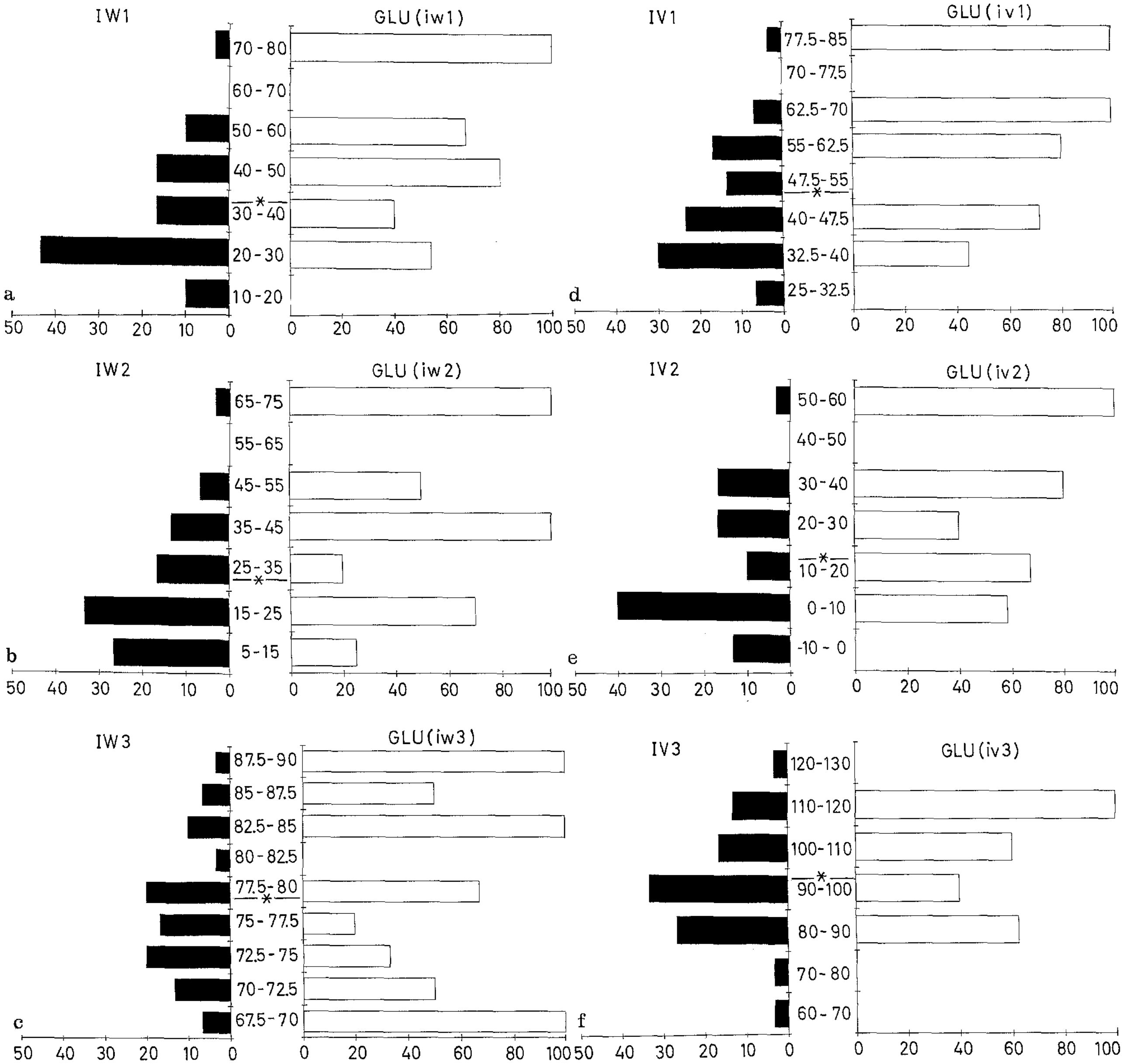

Fig. 1a–f. Distribution of the values of the six selection indices (*left side*) observed from the 30 F_4 lines and the corresponding frequency of the lines having their quality index IQ higher than m+SE (*right side*). **a** IW_1, **b** IW_2, **c** IW_3, **d** IV_1, **e** IV_2, **f** IV_3. * Limit value m+SE of the selection index

Table 8. Percentages of the lines selected using the index (IW_i or IV_i) that were also independently selected with only one parameter. The m+SE limit values for selection indices and the parameters are given in Fig. 1 and Table 7, respectively

Indices	Pro	Pel	Zym	Mixo					IQ
				MTM	MHM	MH7	MT7	MIN	
IW_1	41.6	100.0	83.3	83.3	58.3	50.0	58.3	75.0	50.0
IW_2	41.6	100.0	83.3	83.3	58.3	50.0	58.3	75.0	50.0
IW_3	60.0	70.0	80.0	60.0	80.0	80.0	70.0	60.0	50.0
IV_1	45.5	100.0	90.9	81.8	63.6	54.5	63.6	81.8	54.5
IV_2	41.6	100.0	83.3	83.3	58.3	50.0	58.3	75.0	50.0
IV_3	33.3	66.6	58.3	75.0	58.3	66.6	66.6	66.6	50.0

sequently, the distributions of IW_1, IW_2, IV_1 and IV_2 indices which included the Pelshenke test, were asymmetrical (Fig. 1a, b, d and e respectively). Indices IW_3 and IV_3 were normally distributed. The proportions of the lines having $IQ > m+SE$ in each quality class of the indices IW_i or IV_i showed the following (Fig. 1).

(1) All lines having the highest IW_i or IV_i values also had a high IQ.

(2) On the other hand, many lines selected with IQ ($IQ > m+SE$) would have been discarded through the selection indices (IW_i or $IV_i < m_i+SE_i$). The proportions of these lines expressed as percent of discarded lines is the same for all the selection indices and is about 54%.

(3) The proportions of the lines selected by using the selection indices, which then should have been discarded by the index IQ ($IQ < m+SE$), were the following: IW_1: 41.7%; IW_2: 41.7%; IW_3: 40%; IV_1: 30%; IV_2: 41.7% and IV_3: 50% (expressed in percent of the selected lines). Although the index IQ was correlated with five indices, the potentialities of quality it evaluated do not correspond to all of the variability measured by the different parameters used in the selection indices.

Discussion

The quality indice IQ was strongly correlated with the gluten score GS published by Payne et al. 1987; Payne 1987. The GS was essentially established from comparisons of SDS sedimentation values, whereas IQ was calculated from different parameters of rheology and from dough swelling time of the Pelshenke test. The allelic effects, which correspond to the average of the differences between the quality values of the genotypes having a given allele and those having the reference allele, represent the true additive effects attributable to present-day European bread wheats. These effects would have been different if the genetic origin of the 195 wheats was less diversified. The simple statistical method used for calculating the IQ coefficient can be used for developing other IQs more adapted to the cultivars and to the quality objective of a given country.

Few cultivars had the alleles *Glu-B1e* (band 20) and *Glu-D1e* (bands 2–11). Consequently, these alleles were not introduced into the comparison of the means (Table 5). Their effects were estimated by comparing the quality values of the cultivars differing only by their *Glu-B1* or *Glu-D1* alleles. Only two cultivars had the rye secalins; consequently, the effect of the 1BL/1RS translocation on dough stickiness and weakness (Dhaliwal et al. 1988) was not reported. Using the same parameters we have studied the effects of the 1BL/1RS translocation on another set of cultivars and calculated the coefficient attributed to the indice IQ (unpublished).

Many studies have been conducted to evaluate the efficiency of the index of selection in several crops for improving different characters: grain yield in maize (Robinson et al. 1951), wheat (Smith 1936), barley (England 1977) and oats (Eagles and Frey 1974), and for many other genetic traits as well (see Baker 1986 for review). In many cases it was demonstrated that introducing the character to be improved as a parameter of the index increased the relative efficiency of the index. In our case the strength W and loaf volume LV were not introduced in the index. All of the parameters used in the six indices contributed to a significant explanation of the character W or LV to improve. Moreover, for the three tests Pel, Zym and Mixo at least one of their parameters had a greater expected response to increase in the mean genotypic values of W or LV when combined in the index than it should have if used alone. As the alveograph and the baking test were not performed on the 30 lines, the superiority of the genetic values for the W or the LV of the selected lines was not confirmed. Nevertheless, for IW_1, IW_2 and IV_1 or IV_2, 75–100% of the selected lines using these indices were also selected by the parameters Pel, Zym and Min. These percentages dropped to 58 to 60% when the mixograph was combined with Pro. As the index integrates several parameters, each corresponding to different technological properties, the observed complementation of IW_i or IV_i with the index IQ seems to be obvious. To determine the maximum efficiency for breeding, in using first the HMW-GS analysis, then the technological evaluations, more studies are needed. However, our results confirm what P. Kolster (personal communication) showed by selection with the HMW-GS profile and the SDS sedimentation test: breeding on the HMW-GS profile may lead to the elimination of many lines that would not have been discarded using a technological test. Consequently, for minimizing the losses of good quality lines when screening first from HMW-GS, it seems advisable to retain genotypes of IQ values higher than the mean m of the population rather than $m+SE$.

Several criteria may be more important than others in choosing the most appropriate index from the six selection indices studied. From 10 to 25 g of grain are needed for the technological tests used in our indices. For the small-scale computerized mixograph, which helps wheat breeders test earlier generations (Rath et al. 1990), these amounts can be reduced. The mixograph initially developed for clarifying the dough characteristics in order to produce an optimum loaf (Swanson and Working 1933; Finney and Shogren 1972) also has parameters both correlated to strength and heritable (Branlard et al. 1991). However, the mixograph is less capable of evaluating the poor quality wheats than the Pelshenke test. Thus, there are some advantages to using indices IW_2 and IV_2.

Conclusion

Each year breeders use several technological tests for assessing quality without relating them in a selection index that would provide more information on the genetic value of their material. For the first time breeding indices are proposed for the quality evaluation of bread wheats. According to quality objectives, these indices can be used in early generations in addition to HMW-GS determination. The indices IW and IV may be combined in a global index $I = pIW + qIV$ where $p = 1 - q$ is chosen according to the priority of breeding. Many other selection indices could be created for wheat quality; among these, the introduction of the SDS sedimentation test as an alternative to the Zeleny, and grain hardness could be very useful for the further improvements.

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