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WORKER INTERDEPENDENCE AND OUTPUT: THE HAWTHORNE STUDIES REEVALUATED*

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Recent work has called into question the “human relations” interpretation of the evidence from the classic Hawthorne studies, arguing that external factors suffice to explain the variation in workers’ output found at the Hawthorne plant. In contrast, this paper demonstrates that, allowing for a wide range of other factors mediated by the social interactions in the working group, workers’ productivity levels in the Hawthorne plant were indeed interdependent. Using five years of weekly data from the original Hawthorne studies, a structural model of worker productivity is estimated. This model allows for interdependence of workers’ output levels, while recognizing that, although mediated by small group interactions, external and experimental variables can also play a role. The results reveal the joint importance of external factors and worker interaction in affecting the level and variability of output. The human relations approach to industrial sociology is not controverted by the original Hawthorne data from which it began.

The Hawthorne studies of the late 1920s and early 1930s have had widespread influence in industrial sociology and provide the foundation for the sub-fields of human relations, organizational development and organizational design (Roethlisberger and Dickson 1939; Whitehead 1938; Homans 1951). Beginning with what in retrospect appear to be naive attempts to relate worker productivity to the intensity of illumination in the Hawthorne plant of Western Electric, the studies elaborated the role of social interaction in the determination of work effort and output levels. The increasing complexity of such interactions that the Hawthorne researchers found and explored—first in the Illumination and the Relay Room experiments, later in the Mica Splitting Test Room and the Bank Wiring Observation Room—changed many ways of thinking about the labor process and, whatever the current status of the Hawthorne studies themselves, altered forever the landscape of industrial sociology. Major works

of appraisal include Landsberger (1958), Dickson and Roethlisberger (1966), Carey (1967), and Cass and Zimmer (1975).

In important recent work, Franke and Kaul (1978) re-examined the evidence collected at the Hawthorne plant, particularly the data from the “Relay Assembly Test Room.” Using the original sources to construct data series for individual worker output levels and related variables, they conducted a statistical analysis of the determinants of the quantity of output over the five-year study period. Whereas the original Hawthorne researchers had found striking evidence for the interdependence of work patterns in small industrial groups, Franke and Kaul’s principal finding was that experimental control variables, together with external factors such as impending economic adversity and raw materials problems, could explain almost all of the recorded variation in output, thereby “obviating the need to draw upon less clearly definable human relations mechanisms” (p. 623). These conclusions gave rise to a lively debate (Wardwell 1979; Franke 1979, 1980; Schlaifer 1980) on their statistical procedures. Questions were also raised about the original interpretation of variables such as “managerial discipline” (the replacement of two workers by two others early on in the Relay Room study) and “economic depression” (a dichotomous variable representing the onset of the great Depression). Overall, while this debate generated some refinements—both in the statistical analysis

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and, more importantly, by the use of weekly output data, rather than averages over experimental periods of varying length — it is unclear that the central issues were resolved.

In the work of Franke and Kaul, an opposition is established between human relations issues on the one hand and external and experimental factors on the other. This opposition has, implicitly, also been accepted by their critics. I argue, however, that most of this debate was misplaced and that this alleged opposition is false. Rather, it is necessary to treat the various experimental and external changes *within* a framework of potentially interdependent effort and output decisions by the workers. In this way, one can test for the worker interdependence that was a central finding of the original Hawthorne research. This approach recognizes the role of external factors in affecting worker decisions but insists that these factors be understood as mediated through small group interaction. That is, the presence of small group interaction alters worker responses to environmental change, and is critical for understanding the dependence of output upon these environmental factors, the issue with which the Hawthorne studies began. There is also inherent interest in understanding the nature of within-group social interaction and its effects on levels of effort and output; this in fact became the focus of the Hawthorne studies in their later years.

The goal of this paper, then, is to study the interdependence among worker output levels as recorded in the Relay Assembly Test Room during the 1927-1932 period. Building on the pathbreaking work of Franke and Kaul (1978) and Franke (1980), I use their weekly data and supplement their various experimental and external factors with several other relevant data series extracted from Whitehead's (1938) painstaking empirical study.

THE STUDY OF THE INTERDEPENDENCE OF WORKER OUTPUT LEVELS

I begin by expositing a simple model of the determinants of worker output levels in which $q_i(t)$ denotes the output level of worker i in period t and $i = 1, 2, \dots, N$ indexes workers in a group of size N . Let $Z(t)$ represent those variables that, in period t , are common to all workers in the group; this includes both external variables, such as economic conditions outside the workplace, as well as internal (potentially experimental) variables such as the quality of raw

materials, the pay and incentive schemes common to all group members, and variation in scheduled rest stops. Further, let $X_i(t)$ denote other variables that are specific to worker i in period t , examples being (idiosyncratic) voluntary rest time or a dichotomous (dummy) representation of whether or not that worker was recorded as sick.

Specifically, I take $N = 5$, as in the Relay Assembly Room, and focus on the output of worker 1, $q_1(t)$. Suppose that during a given time period, worker 1 gradually adjusts her output toward a personal target level, denoted as $q_1^*(t)$. That is,

$$q_1(t) - q_1(t-1) = \lambda_1 [q_1^*(t) - q_1(t-1)] \quad (1)$$

where $q_1(t-1)$ is the actual output level of worker 1 recorded in the preceding period, $t-1$, and λ_1 is the degree to which worker 1 closes a gap between her target and the previous period's output. Rearranging equation (1) yields

$$q_1(t) = (1-\lambda_1) q_1(t-1) + \lambda_1 q_1^*(t) \quad (2)$$

so that current output of worker 1 is just a weighted average of her output level in the preceding period and the target output level, with the relative weights depending on the speed of adjustment, λ_1 . This partial adjustment framework is a natural way of thinking about patterns and habits of work that alter slowly over time, where the response to some environmental change can be greater as a worker becomes adapted to it (see Nerlove 1956; Judge, Griffiths, Hill, Lüdtkepohl, and Lee 1985, chapter 10).

The target output level $q_1^*(t)$ itself is assumed to be determined by three sets of factors: the variables common to all workers, $Z(t)$; the variables specific to worker 1, $X_1(t)$; and the output levels of the other members of the work group, $q_2(t), \dots, q_5(t)$. In addition, this target equation may contain a person-specific error term, $u_1(t)$, which is assumed to be serially independent. The target equation is hence

$$q_1^*(t) = a_1 + b_1 Z(t) + c_1 X_1(t) + \alpha_{12} q_2(t) + \alpha_{13} q_3(t) + \alpha_{14} q_4(t) + \alpha_{15} q_5(t) + u_1(t) \quad (3)$$

where a_1 is an intercept, b_1 and c_1 are slope coefficients for the common variables and worker-specific variables respectively, and $\alpha_{12},$

..., α_{15} are slope coefficients for the dependence of worker 1's target output on other workers' output levels. This potential interdependence of worker output levels is the novel statistical feature of this paper. Such interdependence may arise for the sociological reasons discussed by the early Hawthorne researchers, or for other more strategic reasons such as those associated with the nature of particular pay and incentive schemes (e.g. Mathewson 1931; Roy 1952). Interdependence may also arise for technological reasons, as on a production line where workers' output levels are necessarily interdependent, although this type of interdependence was not in fact present in the Relay Assembly Room. For a specific model of interdependence in a similar framework to that used here, see Jones (1984).

Using equation 3 in equation 2, one can eliminate the target variable $q_1^*(t)$ and express the current output level of worker 1 in period t as depending upon her own past output level, the sets of Z and X_i variables, and the current output levels of the other members of the working group:

$$q_1(t) = (1-\lambda_1) q_1(t-1) + \lambda_1 [a_1 + b_1 Z(t) + c_1 X_1(t) + \alpha_{12} q_2(t) + \alpha_{13} q_3(t) + \alpha_{14} q_4(t) + \alpha_{15} q_5(t)] + \lambda_1 u_1(t) \quad (4)$$

The general case of equation 4 (which gives the equations for each of the other four group members) can be specified as

$$q_i(t) = (1-\lambda_i) q_i(t-1) + \lambda_i [a_i + b_i Z(t) + c_i X_i(t) + \alpha_{.i} q_{.i}(t)] + \lambda_i u_i(t) \quad (5)$$

for $i = 1, 2, \dots, 5$, where $\alpha_{.i}$ is a vector of coefficients corresponding to the output levels of group members other than worker i , here denoted $q_{.i}(t)$. Equation 5 is the basis for statistical modelling of the interdependence of output levels below.¹ The error terms, $u_i(t)$, are each serially independent, as assumed above, but there may be contemporaneous correlation across these equations; this will be a factor when system estimates are presented below.

¹ Case, Hines, and Rosen (1989) is a model of interdependent spending decisions by state legislatures in the US that has a similar statistical structure.

It is clear from equation 5 that the issue of intertwined cause and effect is potentially present here. A single equation, such as equation 5, does not permit determination of the independent effect of, say, $q_2(t)$ upon $q_1(t)$ as distinct from the reverse and simultaneous effect that $q_1(t)$ may have upon $q_2(t)$. This cause and effect problem may in part explain why no one has heretofore addressed the central conclusion of the Hawthorne study statistically.

However, simple procedures are available to obtain consistent estimates of parameters such as these, provided suitable "instrumental variables" can be found. The problem of identifying cause and effect is that all output levels are determined simultaneously, according to equation 5. To identify the coefficient on worker 2's output, $q_2(t)$, in the equation determining the output of worker 1, $q_1(t)$, one needs to discover a variable that affects worker 2's output *without* also directly affecting the output of worker 1. Variation in this factor will then cause worker 2's output to alter for a reason not caused by variation in 1's output and the resulting changes in the output of worker 2, $q_2(t)$, will affect worker 1's output, $q_1(t)$, in a way that can be estimated. Such a variable is said to be *excluded* from the equation determining the output of worker 1, here equation 4 above, and constitutes an *instrumental variable* for worker 2's output in the equation for worker 1. This idea generalizes readily to any number of equations, provided that in each case instrumental variables can be found that are legitimately excluded from the equation of interest.

In the present case, there are two ready sets of candidate instruments. First, the *past* output level of a worker affects that worker's *current* output decision but is not itself affected by other workers' *current* output levels; thus, $q_2(t-1)$ can be an instrument for $q_2(t)$ in the equation for worker 1, and so on. Second, the person-specific variables, $X_2(t)$, for example, affect $q_2(t)$ but do not have any direct influence upon $q_1(t)$, according to equations 4 and 5, and can therefore also serve as instruments.

DATA AND METHOD

Data to be analyzed are drawn from weekly records collected from April, 1927 to June, 1932 at the Hawthorne plant of Western Electric. In the Relay Assembly Test Room, the focus of the present study, five women worked, in a technologically independent way, producing electrical

relays. Detailed descriptions of the backgrounds of these workers, the physical conditions in the room, the technology and various incidents that occurred during the study may be found in Roethlisberger and Dickson (1939, especially Chapters II-VIII) and Whitehead (1938). The process of selecting workers for the study does not seem to have been systematic (Whitehead calls it "quite informal and somewhat obscure" (1938, Volume I, p. 14)), except that some experience in this line of work was expected, and that the workers were all volunteers. Further, "they were expressly cautioned to work at a comfortable pace, and under no circumstances to try and make a race out of the test," according to the words of the Relay Room superintendent (Whitehead 1938, Volume I, p. 104).

The five women who worked in the relay room for most of the study period were quite young. Workers 1-4 were between 20 and 22 years of age at the start of 1930 and worker 5 was 31 (Whitehead 1938, Volume I, Table II, p. 16). Workers 1-4 had been born in the United States, worker 2 being of Italian extraction and workers 1, 3 and 4 being of Polish origin. Worker 5 had immigrated to the U.S. from Norway at age 25 and was the only married member of the group. All of the women had prior experience assembling relays, as noted above, but the extent of this varied from worker 5 with only 13 months experience to worker 2 at 47 months. The differing personality characteristics of the five women are best summarized by Roethlisberger and Dickson: "the docile submission of Operator 1, the restless impatience of Operator 2, the moodiness of Operator 3, the sturdy independence of Operator 4, and the aloofness of Operator 5" (1939, pp. 170-71).

Output figures employed are the weekly average number of relays produced per hour per worker.² These data are taken from Franke (1980, Appendix 1) and are preferable to the averages

across experimental periods of varying length that were used in his 1978 and 1979 statistical analyses. Also available are individual data on machine repair time and voluntary rest time, measured in minutes per day. Both of these series are based on experimental period averages (Franke and Kaul 1978, Appendix 2), coded here as the relevant weekly average within an experimental period. These data are supplemented by a set of dichotomous variables representing whether or not each worker reported having felt ill while at work during the week in question. These data were constructed from tables in Whitehead (1938, Volume I, Chapter 7) and are based on worker retrospection during regular medical check-ups administered to the women. It is noted by Whitehead that the doctor's reports do not give this information after December 1930 and give it only once for all of 1927. Accordingly, these individual-specific dummy variables are supplemented by a dichotomous variable that represents whether or not the doctor was reporting such events at the time, and it is assumed that s/he was not doing so in 1927 and for all of 1931 and 1932.

In addition, a set of variables, Z, that affect all workers' output levels is included. This set includes a weekly series of days worked per week (Franke 1980, Appendix 1) and a measure of "raw materials problems" (Franke and Kaul 1980, Appendix 1). This latter source also provides data on scheduled rest time, measured in minutes per day, a variable that was changed as part of the experimental design in the Relay Room (see Roethlisberger and Dickson 1939, Chapter III). Allowance is made for incomplete data by including a dummy variable denoting weeks when the data on scheduled rest stops were missing. Finally, there is a dummy variable describing the pay and incentive system in operation in the Relay Assembly Room. For the period under study, payment was based on a "group piece rate," whereby a rate was applied to the output of the group as a whole (with allowance for "carrying" the layout operator); this total group remuneration was then distributed among the group members according to each worker's "individual rating" which depended on assessed skill and length of service (Whitehead 1938, Volume I, p. 17). In the first seven weeks of the 270 week study, the piece rate was applied to the output of a group with over 100 members, but thereafter the rate was applied to the output of the small group in the Relay Assembly Room itself (Roethlisberger

² In fact, the women produced over 200 different types of relays, although in many cases the differences among types were slight (Whitehead, 1938, Volume I, p. 18). For present purposes, the data employed follow the Western Electric Company's own practice, used for its pay system, of converting the outputs of various types of relays into the output of a standard relay. Detailed discussion of the potential biases this might introduce is presented in Whitehead (1938, Volume I, Chapter 9), where it is concluded that changing relay types had essentially no effect on the overall output of experienced employees.

and Dickson, 1939, p. 34).³ A dummy variable represents this change; it was labelled "X15" and termed "Small Group Incentive" in Franke and Kaul (1978) and the debate cited above.

The U.S. national unemployment rate in each year of the study (U.S. Bureau of the Census 1975, part 1, p.135) is used as a better measure of changing external economic conditions than the "economic depression" dummy variable employed in earlier work.⁴ A dichotomous variable represents weeks in which the usual seating arrangement in the relay room was changed (Whitehead 1938, Volume I, p. 147 ff.), which happened during a ten month period starting in April, 1930. Lastly, two dummy variables are included that take the value 1 if the *Chicago Tribune* reported a heat wave or a cold wave in the week in question (Whitehead 1938, Volume I, Appendix). Whitehead suggests that, while heating arrangements were adequate, so that external cold temperatures did not lead to unusually cold conditions within the relay assembly room, very hot and humid weather led to a worsening of working conditions in some weeks during the summers.

While the principal source of variation in these variables during the early part of study period was conscious experimentation, for most of the period the changes that can be exploited statistically are better characterized as expedient responses to the onset of the Depression (Whitehead 1938, Volume I, p. 38). Research attention in the later years was focused on other aspects of the Hawthorne studies, such as the Bank Wiring Observation Room, and the changes present in the data (e.g., Saturday mornings off, a 4:15pm end to the working day) were as much the result of changing conditions as of explicit design.

Finally, it is important to remember that the composition of the Relay Assembly Room working group changed during the 270 weeks

³ According to the contemporary accounts, the workers valued the insurance aspect of the group remuneration and tended to dislike the lack of work incentives in the large group case (Whitehead, 1938, Volume I, p.133). The change to a smaller group for payment purposes was welcomed by the group members, with the latter incentive effect being improved while the mutual insurance motive was still, in their minds, met (Whitehead, 1938, Volume I, p.255).

⁴ It is worth noting that the Relay Assembly Room study ended in 1932 with the five workers being laid off as a direct result of the Depression.

under study. After week 39, workers 1A and 2A were permanently replaced by workers 1 and 2. Also, during weeks 120 to 160, and from week 255 to the end of the study, worker 5 was replaced by worker 5A. Workers 3 and 4 were present in the Relay Room for the whole study period, except for vacations and minor short-term absences.⁵ To deal with the issue of changing composition, two methods of analysis are employed.

First, I estimate a model of the determination of output for each worker separately using only those weeks when the worker in question was actually in the Relay Room; this leads to varying sample sizes, of course, reflecting the differences in the number of weeks that the five workers were in fact present.⁶ To accommodate the personnel changes, which provide one natural experiment for the interdependent output model, dummy variables representing the personnel change and interaction terms of these dummy variables with the output levels of workers 1/1A, 2/2A and 5/5A are included in the equations for the outputs of the other workers. This allows for both a change in the intercept and a change in the (slope) interdependence coefficient whenever the group composition changes, and is preferable to a simple shift dummy variable (as used by Franke and Kaul, 1978, for example) in that it allows changing interdependence effects (Maddala 1977, Chapter 9). Second, as an alternative procedure, I restrict attention to those periods when the five members of the core group (workers 1, 2, 3, 4 and 5) were present, thereby removing all complications of changing group composition. With the adjustment for lagged output variables, this yields a consistent sample size of 159 weekly observations.

⁵ Omitted from the sample are all weeks in which any worker lacked either a valid output figure or a valid output figure for the preceding week. This leads to the omission of the six synchronized vacation periods during the time of the study, as well as a small number of other weeks when one or more of the workers was absent.

⁶ The key point is simply that, to model the behavior of, say, worker 5, only worker 5's behavior should be analyzed, and not that of her replacement 5A. This was apparently not appreciated by Franke (1980), however, where "individual" models of output are estimated using composite data of precisely this type. As a consequence, the interpretation of results for "individuals" 1A + 1, 2A + 2, and 5 + 5A in his Tables 4, 5, and 6 is highly problematic.

Table 1. Summary Statistics for all Variables: Five Workers in the Relay Assembly Room, 1927-1932

Variable	Mean	Standard Deviation	Range	
			Minimum	Maximum
Output of 1/1A	67.19	7.17	46.40	80.00
Output of 2/2A	70.46	8.36	45.60	82.40
Output of 3	63.45	4.33	43.70	72.90
Output of 4	67.54	6.77	48.10	82.40
Output of 5/5A	59.20	5.72	43.40	69.40
Repair time of 1/1A	27.51	14.01	.00	59.90
Repair time of 2/2A	22.79	10.67	.00	42.70
Repair time of 3	20.34	11.38	.00	40.70
Repair time of 4	11.79	7.68	.00	30.00
Repair time of 5/5A	23.29	18.96	.00	69.00
Voluntary rest of 1/1A	5.31	3.77	.00	15.00
Voluntary rest of 2/2A	7.16	4.31	.00	20.60
Voluntary rest of 3	6.23	3.05	.00	13.00
Voluntary rest of 4	7.42	3.80	.00	16.50
Voluntary rest of 5/5A	5.48	2.08	.00	8.90
Worker 1 ill	.08	.27	0	1
Worker 2 ill	.06	.24	0	1
Worker 3 ill	.06	.24	0	1
Worker 4 ill	.05	.22	0	1
Worker 5/5A ill	.03	.16	0	1
Scheduled rest time	21.46	8.80	.00	30.00
Days per week	5.03	.58	3.00	5.50
Raw materials problems	.15	.36	0	1
Seating change	.17	.38	0	1
Unemployment rate	8.40	6.18	3.20	23.60
Heat wave	.04	.20	0	1
Cold wave	.04	.19	0	1
Small group pay	.97	.16	0	1
1A & 2A replacement	.13	.33	0	1
5A replacement	.21	.41	0	1
No medical reports	.38	.49	0	1
No scheduled rest stop reports	.04	.20	0	1

Notes: N = 239. The sample omits the 31 weeks in which at least one of the workers was absent from the work group or had been absent the preceding week.

Table 1 contains summary information on all variables used in the analysis, excluding those periods (mostly annual vacations) when at least one of the workers was absent from the relay room or had been absent during the preceding week.

ESTIMATES OF THE INTERDEPENDENCE OF WORKER OUTPUT LEVELS

Individual Equation Estimates using Varying Sample Periods

I have estimated equation 5 for each worker using both ordinary least squares and two-stage

least squares, the latter procedure allowing for the potential endogeneity of other workers' output levels. For both procedures, all weeks in which the worker concerned was present are used, and interaction variables are included that are the workers' output levels multiplied by a dummy variable representing the replacement. This allows the slope coefficient — which shows how worker *i*'s output affects the output of worker *j* — to vary as workers are replaced. In addition, I use a standard additive dummy variable that allows the intercept of the equation to be affected by the replacement. Since the "cause and effect" problem mentioned above is likely important, I report only the two-stage least

Table 2. Two-Stage Least Squares Results for the Relationship Between Worker Output and Selected Variables

Variable	Output of Worker				
	1	2	3	4	5
Own lagged output	.14* (.06)	.22** (.06)	.00 (.05)	.10* (.04)	.18** (.04)
Output of 1/1A	----	.48** (.12)	.33 (.23)	-.33 (.25)	.04 (.23)
Output of 2/2A	.53** (.16)	----	-.31 (.22)	.56** (.18)	.44* (.19)
Output of 3	.09 (.24)	-.44* (.19)	----	.72** (.19)	-.09 (.30)
Output of 4	-.03 (.21)	.38* (.16)	.64** (.18)	----	.10 (.21)
Output of 5/5A	.16 (.13)	.18 (.13)	-.20 (.15)	.24 (.18)	----
Worker 1 interaction	----	----	-.38 (.35)	.31 (.38)	.12 (.35)
Worker 2 interaction	----	----	.41 (.29)	-.54 (.33)	-.07 (.32)
Worker 5 interaction	-.07 (.14)	-.08 (.14)	.13 (.23)	-.34* (.17)	----
Repair time of i	.04* (.02)	-.04 (.03)	-.05† (.03)	.02 (.04)	.03 (.04)
Voluntary rest of i	-.19 (.18)	.30* (.13)	.02 (.08)	-.06 (.09)	-.20 (.16)
Worker i ill	.36 (.48)	-.16 (.50)	-.93 (.58)	.53 (.74)	-.74 (.91)
Scheduled rest time	-.10 (.11)	.22** (.07)	.07† (.04)	-.02 (.05)	-.07 (.06)
Days per week	.44 (.41)	.61 (.39)	-.09 (.43)	.51 (.48)	-1.51** (.44)
Raw materials problems	-1.19 (1.22)	1.75 (1.19)	-1.95 (1.28)	2.17† (1.28)	-4.46† (2.41)
Seating change	-2.05* (.83)	2.88** (.91)	-.51 (.90)	1.22 (.98)	-1.81† (1.04)
Unemployment rate	.28** (.09)	-.13 (.10)	.13 (.12)	-.00 (.14)	.24† (.13)
Heat wave	-.93 (.70)	.59 (.66)	.09 (.74)	-.52 (.84)	-.69 (.76)
Cold wave	1.58† (.87)	-2.79** (.69)	-1.53† (.81)	1.65† (.89)	.52 (.98)
Small group pay	----	----	3.51* (1.48)	-1.35 (1.83)	.99 (2.30)
1A & 2A replacement	----	----	-2.56 (14.19)	14.87 (12.74)	1.15 (14.51)
5/5A replacement	5.11 (8.46)	5.78 (8.16)	-6.61 (13.95)	19.02† (10.29)	----
Constant	5.03 (9.57)	4.00 (9.19)	27.17** (7.09)	-17.14 (10.54)	22.44* (11.31)
R ²	.84	.89	.82	.90	.88
s.e.e.	1.85	1.72	1.94	2.33	2.01
d.f.	189	189	216	216	168
Wald $\chi^2(4)$	26.34**	67.56**	32.17**	79.00**	41.55**
Hausman $\chi^2(4)$	3.53	4.98	6.81	2.87	12.05**

† $p < .10$ * $p < .05$ ** $p < .01$

Notes: Values in parentheses are standard errors. Control variables included in the estimating equations but whose coefficients are not shown are "No Medical Reports" and "No Report on Scheduled Rest Stops." The Wald χ^2 statistic tests the hypothesis that all other workers' output levels jointly be excluded from the equation. The Hausman χ^2 statistic tests the hypothesis that all other workers' output levels are exogenous, given the set of instrumental variables being used.

squares results in Table 2, the ordinary least squares results being available in the working paper version (Jones 1989, Table 2).

For all of workers except worker 3, the lagged own output variable has a significant and positive coefficient, with the significant point estimates implying that between 78 and 90 percent of the gap between target and actual output is made up in one week. In every case, a Wald test of the joint exclusion of the four other contemporaneous output levels strongly rejects that hypothesis. The most striking features of the pattern of coefficient estimates for the interdependence variables are the relative unimportance of worker 5 in determining the other workers' output levels and the near-symmetry of the estimated effects in many other cases: about equal positive effects are seen between workers 1 and 2, 2 and 4, and 3 and 4, while workers 2 and 3 have similar negative effects on one another.

The external and experimental variables have a moderate but significant role to play. The unemployment rate has a positive effect for worker 1 and, less convincingly, for worker 5, but has insignificant coefficients for workers 2, 3 and 4 (though the coefficient for worker 2 is significantly negative in the ordinary least squares case). These findings stand in contrast to the central role of the "economic depression" dummy variable used by Franke and Kaul, the discrepancy being probably explained by the broader set of other factors used here and by the fact that the unemployment rate is a better measure of a changing economic climate than the step variable used in the earlier work. Similarly, the seating change variable and the indicator of extremely cold weather are sometimes significant, but with conflicting signs.⁷ The various person-specific controls, especially repair time and voluntary rest time, are important for some workers, although again the pattern of the signs of the coefficients is mixed. The worker replacement interaction terms and the additive dummy variables representing the various personnel changes are mostly unimportant. Only the temporary replacement of worker 5 by worker 5A has any role to play and even then these coefficients are only significant for worker 4. Finally, I note that although there are some

⁷ Note that only worker 2, of Italian extraction, was negatively affected by extreme cold weather, according to these results, while the workers of Polish origin (workers 1, 3 and 4) and the worker from Norway (worker 5) were comparatively unaffected.

differences between the Table 2 results and the ordinary least squares estimates reported in Jones (1989, Table 2), these differences are mostly not striking. A formal Hausman (1978) test of the exogeneity of the other workers' output levels, based on the validity of the chosen set of instruments, leads to rejection of the null hypothesis of exogeneity only for worker 5.

Estimates using a Consistent Sample Period

I now address the estimates using *only* weeks in which all five main group members were present. This avoids the issue of whether the introduction of a replacement worker altered the interactions between other group members. Using this consistent sample of 159 weekly observations, the five equations can be estimated jointly and I can thereby test various *joint* hypotheses ("cross-equation restrictions") about the patterns of worker interdependencies.⁸ Since the focus is on the interdependence of worker output levels, only these results are henceforth reported (the complete set of coefficient estimates and standard errors for the other variables is available upon request). Also, since the equation by equation results using the consistent sample largely replicate the results of Table 2, they are relegated to the working paper version (Jones 1989, Appendix).

Table 3 reports three-stage least squares estimates for the unconstrained system; overall, these are broadly comparable to the two-stage least squares figures in Table 2 (and in Jones 1989, Appendix). This procedure exploits the potential overidentification of the system when both lagged output and person-specific instrumental variables are used and leads to greater efficiency when the error terms in the constituent equations are correlated (Maddala 1977, pp. 482-86).⁹ The lagged dependent variable effects are somewhat similar, although the point estimates are generally smaller than previously. Worker 2 has a coefficient on her own lagged

⁸ Since there are no longer group composition changes, the interaction variables that represented these changes are omitted. The seating change variable is also excluded, since this was associated with worker 5 being temporarily replaced by worker 5A.

⁹ A Breusch-Pagan test that the variance-covariance matrix is diagonal yields a $\chi^2(10)$ statistic of 234.43, a very strong rejection of this hypothesis. This suggests that the three-stage least squares estimates are more efficient than the earlier figures that came from estimating each equation separately.

Table 3. Three-Stage Least Squares Estimates of the Interdependence of Worker Output Levels

Variable	Output of Worker				
	1	2	3	4	5
Own lagged output	.10 (.07)	.08 [†] (.05)	.18* (.08)	-.00 (.04)	.48** (.07)
Output of 1	----	.64** (.13)	.30* (.13)	-.78** (.18)	.12 (.15)
Output of 2	.61** (.15)	----	-.35** (.12)	.98** (.10)	.32* (.14)
Output of 3	.84** (.25)	-.84** (.17)	----	1.01** (.19)	.19 (.23)
Output of 4	-.69** (.20)	.89** (.09)	.60** (.11)	----	-.16 (.18)
Output of 5	.18 (.13)	.00 (.12)	-.11 (.10)	.07 (.15)	----
$\chi^2(4)$ tests of restrictions that:					
No one affects worker 1		31.31**			
No one affects worker 2		237.35**			
No one affects worker 3		35.34**			
No one affects worker 4		218.75**			
No one affects worker 5		25.13**			
No one is affected by worker 1		29.22**			
No one is affected by worker 2		107.13**			
No one is affected by worker 3		34.96**			
No one is affected by worker 4		137.70**			
No one is affected by worker 5		3.46			
$\chi^2(20)$ joint exclusion test:		734.41**			

[†] $p < .10$ * $p < .05$ ** $p < .01$

Notes: Values in parentheses are standard errors. Estimates are based on the consistent sample of 159 weeks. Control variables included in the estimating equations but whose coefficients are not shown are "No Medical Reports" and "No Report on Scheduled Rest Stops," repair time, voluntary rest time, a dummy variable indicating whether or not worker i was ill, scheduled rest time, days per week, raw materials problems, the unemployment rate, and heat wave and cold wave. The $\chi^2(20)$ statistic tests the hypothesis that all other output variables jointly be excluded from the system of equations.

output variable that is small and significant only at the 10 percent level, while the coefficient on own lagged output is not significantly different from zero for workers 1 and 4. Of the interdependence coefficients themselves, many are now strongly significant, with positive effects between workers 1 and 2, and 2 and 4, and with negative effects between workers 1 and 4, and 2 and 3.

Two particular sets of hypotheses are tested and the associated $\chi^2(4)$ statistics are reported: that no other worker affects worker i ; and that no other worker is affected by worker i . In the earlier terminology, these tests are respectively that $\alpha_{ij} = 0$ and $\alpha_{ji} = 0$ (for all j not equal to i); this amounts to testing respectively that the last four

elements in each column and the last five rows of the upper panel of Table 3 are zero. In every case, the hypothesis that no one affects worker i is rejected, while in every case but one, the data similarly reject the null hypothesis that no other worker is affected by worker i . The exception is worker 5, for whom the data only reject the null that she affects no one with a p value that just exceeds one half. The joint hypothesis that all of these coefficients are zero, tested by the $\chi^2(20)$ statistic, is strongly rejected. Data from the Relay Assembly Room decisively reject the position that social interactions have no role to play, even when a large set of external and experimental control variables are included.

Finally, several sets of cross-equation restric-

tions were tested for these data in an attempt to encapsulate the findings of Table 3 in a simple representation. Four particular types of constraints were employed: (1) symmetry, that the effect worker *i* has on worker *j*'s output is the same as the effect that worker *j* has on the output of worker *i*: i.e., $\alpha_{ij} = \alpha_{ji}$; (2) the restriction that worker 2 is a leader and worker 1 a follower, as suggested by Roethlisberger and Dickson (1939, p. 167-68), so that $\alpha_{j1} = 0$ and $\alpha_{2j} = 0$; (3) the restriction that all other workers have equal effects on each particular worker, so that, for each worker *i*, $\alpha_{ij} = \alpha_{ik}$; ¹⁰ and (4) the restriction that all equations share a common lag structure, so that $\lambda_i = \lambda_j$ for all workers *i* and *j*. However, each restriction was rejected by the data, with the least decisive rejection (that of the symmetry hypothesis) being almost exactly at the 5 percent level. The constrained system estimates and test statistics are reported in Jones (1989, Appendix).

I also investigated various "location-based" restrictions on the structure of worker interdependence, the idea being that influences might be greater between workers with neighboring positions on the workbench than, say, between workers at opposite ends. Although there is some evidence in the original accounts for this type of effect — it was apparently a factor in the decision to re-arrange the seating plan — it is hard to detect in these data. Restricting the degree of interdependence to be a plausible function of the "distance" between two workers, the various χ^2 statistics always reject the restriction overwhelmingly. In view of the fact that the room was small and that interactions involving all members of the group occurred frequently, the fact that differing personalities and attributes played a larger role than location at the workbench is not surprising.

COMPARISON OF STATISTICAL AND DESCRIPTIVE ACCOUNTS

I now address the similarities and differences between this statistical account of worker interdependence in the Relay Assembly Room and the descriptive accounts given by Whitehead and Roethlisberger and Dickson. The focus is

¹⁰ This is equivalent to entering the average output of the other group members in equation 5, instead of entering their output levels individually. This is the restriction imposed in the theoretical model proposed by Jones (1984, Chapter 3).

on the set of interdependence figures given in Table 3, those from the unconstrained system estimation. Three main findings from Table 3 can be compared with the earlier descriptions. These are (1) the relative independence of worker 5; (2) the significantly positive mutual interdependence between several pairs of workers; and (3) the two pairs of workers with a significantly negative mutual interdependence.¹¹

The isolation of worker 5 is a recurring theme in the original research. She was considerably older than the other workers, the only group member not born in the U.S. (and the only one with a foreign accent) and she was the only married woman in the group. She was "noted for her quiet deliberation, sturdy persistence, and a firm but nonaggressive pursuit of whatever she decided to accomplish" (Roethlisberger and Dickson 1939, p. 169). Moreover, she was never a member of the same sub-group as worker 2, whom the earlier sources describe as the acknowledged leader of the group (Whitehead 1938, Volume I, p. 165). She was excluded from many social gatherings outside the workplace, as when worker 2 invited all of the others to visit her home one evening (Whitehead 1938, Volume I, p. 167). In the plant itself, she regularly responded less to the exhortations of worker 2 than did the other women. These accounts are corroborated by the results in Table 3, in that worker 5 affects no-one and only worker 2's output has an effect on her.

The various positive interdependencies in Table 3, between workers 1 and 2, 2 and 4, and 3 and 4, are also largely reflected in the original accounts. Roethlisberger and Dickson note that worker 1 was subordinate to worker 2 and that when worker 1 returned to her usual place next to worker 2, after an interruption, worker 1 "immediately jumped her output by approximately 7 to 8 relays per hour, keeping in step with her new neighbor, Operator 2" (p. 168).¹²

¹¹ The descriptive accounts, while useful, should be interpreted with some caution since they are clearly incomplete and may have some systematic bias. Compared to the ideal in which the recorder presents "a reasonably balanced picture of a number of important aspects of the given situation," Whitehead himself admitted that "none of the records referring to the Test Room can be said to fall into this highest category" (Whitehead 1938, Volume 1, pp. 106-7).

¹² The immediacy of worker 1's response, according to this account, means that the associated dynamic model should display a fast speed of adjustment. From Table 3, the point value of the estimate

Whitehead notes that workers 1 and 2 became close friends (Whitehead 1938, Volume I, p. 156) and concluded that this pair, like workers 3 and 4, were “definitely intimate” (p. 165). The interdependence of workers 3 and 4 is also borne out in the statistical results, although the (admittedly mild) tendency reported by Whitehead (1938, Volume I, p. 134) of worker 3 to follow the lead of worker 4, rather than *vice versa*, is not evident in Table 3. Similarly, the strong positive interdependence found in the statistical results between workers 2 and 4 accords with the original accounts. Roethlisberger and Dickson note that these two women became increasingly friendly and went to parties together outside the plant (1939, p. 168). Likewise, Whitehead comments that “the real solidarity of the group was achieved when, at the end of 1928, Op. 4 identified herself with Op. 2 and, to some extent, carried Op. 5 with her” (1938, Volume I, p. 134). The only instance of a strong positive interdependence of output levels in the statistical results that is not in line with the descriptive material is that between workers 1 and 3. Even in this case, however, the Hawthorne accounts do not note any hostility between workers 1 and 3; in fact, when the change was made in the seating plan in April, 1930, these two workers were deliberately placed in adjacent positions at the workbench.

Two clear negative interdependencies appear in Table 3, these being between workers 1 and 4 and between workers 2 and 3.¹³ The antipathy between workers 2 and 3 reflects a common theme in the original accounts. Worker 3 had been the group leader prior to the replacement of

of λ , implies that 90 percent of the adjustment by worker 1 would be made within the first week, consistent with the verbal account.

¹³ One potential explanation for negative interdependencies, along the lines of Roy (1952), is that workers sought to restrict output to reduce the likelihood of a piece rate revision. (A clear exposition of this type of dynamic effect in a simplified model with one worker is given by Gibbons (1987).) If worker 2 raised output, for example, then perhaps worker 3 would lower her production, fearing a cut in the price per piece. The difficulties with applying this idea to the present context are threefold. First, there is a striking absence of any direct evidence from the verbal accounts that the threat of such a piece rate revision was a concern among these women, in contrast to the “canny calculators” where “the dollar sign fluttered at the masthead of every machine” in Roy’s machine shop (1952, p. 430). Second, the relay assembly workers’ grounds for fearing a piece rate

workers 1A and 2A by workers 1 and 2, but she apparently lost this role to worker 2 shortly into experimental period 7 (early in 1928): “there is some evidence that she felt this loss of leadership keenly and tried to disguise her disappointment by playing the role of a clown.... Most of her disputes were with Operator 2” (Roethlisberger and Dickson 1939, pp. 168-69). Indeed, the change in seating¹⁴ “removed Op. 3 from the proximity of Op. 2 and gave the latter the two assemblers who had irritated her the least” (Whitehead 1938, Volume I, p. 147). There is little in the descriptive accounts jointly concerning workers 1 and 4, for whom some negative interdependence appears in Table 3, but, as with the positive interaction between workers 1 and 3, the situation is more an absence of corroborative data than the presence of contrary evidence.

Finally, there are two instances where results from the statistical analysis are not consistent with the original Hawthorne accounts. First, worker 4 is characterized by a reciprocal pattern of leading *and* following other group members, according to the present estimates. The leadership role is present to some degree in the descriptive accounts, as when worker 3 joined with worker 4 in resisting the imperatives of newly-arrived worker 2 (Whitehead 1938, Volume I, p. 134), but a strong follower pattern

revision may not have been strong since, in fact, the piece rate was never revised after June, 1927. Third, if, despite all this, fear of a potential revision made sense, then it would seem plausible that such a concern should apply to all of the workers, and not just to two pairs of workers selectively. The conflicting pattern of signs in Table 3 makes it hard to explain interdependence in terms of the likely consequences of “too high” or “too low” group output; see Jones (1984, pp. 28-35) for a fuller treatment, related to the Hawthorne Bank Wiring Observation Room data. While such issues may often be central in studies of the workplace, then, they do not seem to be relevant in the Relay Assembly Room.

An alternative and complementary reason for a negative interdependence is that workers were committed to a target income goal or — equivalently, given the pay system — a target total production goal for the group as a whole, so that slacking off by one induced compensatory greater efforts by another. Although there is brief mention of this type of interdependence in the original accounts, it probably does not explain all of the negative interactions.

¹⁴ The change in seating was from an order of 1, 2, 3, 4, 5A, L to an order of 4, 2, 5A, 3, 1, L, where L represents the layout operator (Whitehead 1938, Volume I, p. 147).

is not supported by the descriptive data. The example most consistent with the statistical results comes when “we saw Op. 4 adopting Op. 2’s sentiments with respect to their work situation and acting as her assistant in spurring the group towards higher, and yet higher, outputs” (Whitehead 1938, Volume I, p. 157). But the view that “Operator 4 was independent in thought and action and never allowed other operators to impose upon her” (Roethlisberger and Dickson 1939, p. 168) is not consistent with the interdependence of output levels reported in Table 3.

Second, according to the descriptive material, worker 2 was the “ablest” of the group, “whether judged by intelligence tests or by any other standard” (Whitehead 1938, Volume I, p. 120) and was seen as “the acknowledged leader of the group” who “often chided another operator who had an abnormal amount of defective relays or who took an excessive amount of personal time out” (Roethlisberger and Dickson 1939, p. 167). She had a particular need for income when she first joined the group, her father having recently been laid off (Whitehead 1938, Volume I, pp. 122-23), and this was one factor in her adoption of a leadership role in the group. Also, there is self-professed evidence that she had motives other than money: as she said early in 1929, “It isn’t so much the money we care about as it is being considered the best and the fastest group” (Whitehead 1938, Volume I, p. 134). This evidence is consistent with her output being the highest, on average (see Table 1), and with the significant coefficients on worker 2’s output in three of the other four equations (worker 5 being the independent exception). It is also consistent with the sum of the coefficients across the rows of Table 3 being largest for worker 2, another indication of her leadership role. However, the dependence of worker 2’s output upon the output levels of the other group members — except that of worker 5 — emerges from the estimates in Table 3. Indeed, it is for worker 2 that the hypothesis that “no one affects her” is rejected most strongly. This latter effect does not line up well with the verbal accounts given by Whitehead and Roethlisberger and Dickson.

Overall, however, there is a high — perhaps surprisingly high — degree of correspondence between the present statistical analysis of worker interdependence and the verbal accounts given by the early Hawthorne researchers. The independence of worker 5, the sympathies and friendships between several pairs of the women, and the antipathies between some others are all

reflected both in the statistical results and in the detailed descriptions of the daily interaction in the Relay Assembly Room. In their “first statistical analysis” of the Hawthorne data, Franke and Kaul rather dismissively termed these prior accounts “little more than opinion” (1978, pp. 623-24). On the present reading, however, these early opinions were in fact remarkably close to the mark.

IMPLICATIONS OF WORKER INTERDEPENDENCE

One final calculation highlights the potential importance of accounting for worker interdependence in an assessment of the role of external and experimental variables upon output. I computed the reduced-form short-run elasticities (proportional changes) of each worker’s output in response to a change in several of the external or experimental variables, using the preferred set of unrestricted system-wide results from the equation estimated for Table 3. This calculation involves solving out the worker interdependence coefficients in the five equations simultaneously in order to write the reduced-form of the system with worker outputs appearing only on the left-hand side of the equations.¹⁵ The resulting figures show the overall response of each worker’s output to a change in the variable in question, taking all of the other workers’ responses and the interdependence of output into account. These are compared with the short-run elasticities that

¹⁵ In matrix notation, the system represented by equation (5) for $i = 1, \dots, 5$ can be written as

$$q = (I - \Lambda) q(-1) + \Lambda [BZ + CX + \alpha q + u]$$

where q is a vector of output levels, $q(-1)$ denotes the corresponding vector of lagged values, and Λ is a diagonal matrix where the diagonal terms are the adjustment coefficients, λ_i . B and C are coefficient matrices corresponding respectively to the vectors of variables Z and X . The vector X is stacked so the C matrix contains many zeroes, representing the exclusion restrictions associated with these person-specific regressors. The intercept term from equation (5) in the text is subsumed into Z as a vector of ones. Finally, α is the matrix of worker interdependence coefficients (with zeroes on the leading diagonal); it is this that must be eliminated to arrive at the reduced-form. That is,

$$q = (I - \Lambda\alpha)^{-1} [(I - \Lambda) q(-1) + \Lambda BZ + \Lambda CX + \Lambda u]$$

where I is a 5-by-5 identity matrix.

Table 4. Implications of Worker Interdependence and Independence For Output Levels: Short-run Effects of Changes in Selected Exogenous Variables

Variable	Worker					Effect of a Separate One Percent (1%) Increase in Each Exogenous Variable on Total Group Output
	1	2	3	4	5	
<i>Interdependence Elasticities</i>						
Unemployment rate	.351	-.280	-.122	.317	-.129	.137
Days per week	.278	.161	-.281	-.186	-1.463	-1.490
Scheduled rest time	-.184	1.445	-.402	-1.692	-3.939	-4.773
Heat wave	.000	.006	-.003	-.007	-.020	-.024
Cold wave	.001	-.001	-.001	.001	-.002	-.001
<i>Independence Elasticities</i>						
Unemployment rate	.065	.032	.042	.086	.031	.255
Days per week	.060	-.005	.043	.044	-.049	.094
Scheduled rest time	.051	.034	.054	.046	.030	.215
Heat wave	-.001	-.000	-.001	-.001	-.000	-.003
Cold wave	.000	-.001	-.000	-.000	-.000	-.002

Notes: All elasticities (proportional changes) are calculated at the sample means. The worker interdependence elasticities are calculated from the unrestricted system estimates (partly reported in Table 3), as explained in the text. The worker independence estimates are calculated from the same model where all worker interdependence effects were constrained to be zero.

result when a restriction of *independence* is imposed,¹⁶ thereby assessing the overall importance of worker interdependence for understanding the effects of the external and experimental variables on worker output.

These various elasticities are computed at the sample means in both cases and are reported in Table 4. In interpreting these figures, it should be borne in mind that they result from the estimated equations, and that these equations are themselves estimated with error. The first panel contains the person-specific elasticities with respect to selected variables for each of the five group members under the interdependence model. The second panel presents the analogous figures when independence is imposed. The differences between these two sets of results are striking, with numerically larger elasticities in the interdependence case for almost all workers and variables; in several cases, even the sign of the response changes. Assuming worker independence, an increase in the unemployment rate, for example, would lead to an increase in

the output of every worker. But when interdependent output levels are taken into account, the effect is actually a sizable increase in the output of worker 1, a smaller increase for worker 4, and decreases for the remaining three group members. Similar erroneous inferences about the signs of the other elasticities would result if one wrongly assumed independence.

As a summary of these effects, I calculated the contemporaneous effect on total group output (measured as relays per hour) that would result from a one percent increase in each of these five variables, again evaluated at the sample mean. The overall effect for the unemployment rate is an increase of .14 percent, according to the estimated model, contrasting with the .26 percent rise from the independent predictions. "Days per week" and the measure of scheduled rest time have strikingly opposite effects in the two cases, with the magnitude of the effect being considerably larger in the interdependence model. The weather variables have similar signs under these two scenarios, although these responses to a one percent change in the incidence of extreme weather conditions are always small. In short, the statistical results show that the structural process generating the reduced form

¹⁶ In the notation of the preceding footnote, this independence restriction is simply that $\alpha = 0$, a matrix all of whose elements are zero.

involves considerable worker interdependence and that the reduced-form elasticities of this system would be very different in the absence of interdependence.

CONCLUSION

This paper has presented a straightforward analysis of worker output levels in the Relay Assembly Room of the Hawthorne plant using precise weekly data over a five year observation period. The central question behind the enquiry has been whether or not the workers' output levels were interdependent, given the external and environmental conditions in which the workers operated. Using instrumental variable techniques to purge the endogeneity of contemporaneous output levels, it was found that, across a wide variety of specifications, the data clearly reject a null hypothesis of independence. Also, the role of external and experimental control variables is much weaker once the presence of worker interdependence is recognized. Several simple descriptions of the nature of this interdependence were tried, but each set of cross-equation restrictions was rejected. Instead, a rich pattern of dependent output decisions emerges, one that reflects the particular situation at the Hawthorne plant and, to some degree, the personalities of the workers in the Relay Assembly Room.

This work supplements that of the original Hawthorne researchers, who did not employ multivariate statistical techniques, and stands in contrast to the work of more recent researchers, who did not investigate the question of interdependence. When current methods of statistical analysis are applied to the original data, the conclusion is that worker output levels were indeed interdependent, even allowing for a host of other factors that may have affected behavior. The human relations approach to industrial sociology is not controverted by the original Hawthorne data from which it began.

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