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# Evidence of a Right-Shift Factor Affecting Infant Hand-Use Preferences From 7 to 11 Months of Age as Revealed by Latent Class Analysis

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**ABSTRACT:** Infant hand-use preferences for apprehending objects were assessed three times at 7, 9, and 11 months of age for 154 infants (79 males) using a reliable and valid procedure. Two classification procedures (differing in Type I classification error rates) were used to identify an infant's preference (right, left, no preference) at each age, and these data were examined using two- and three-group latent class analysis models. These analyses revealed the importance of using a handedness classification procedure with low Type I error rates and evidence of a right-shift factor similar to that expressed in child and adult handedness. Thus, infant hand-use preferences for apprehending objects are likely a developmental precursor of adult handedness. The relation of the right-shift factor to increased susceptibility to social influences during development and the evolution of human abilities also is discussed. © 2002 John Wiley & Sons, Inc. *Dev Psychobiol* 40: 1–13, 2002

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When performing both simple and sophisticated motor tasks, most individuals exhibit a clear preference for the use of one hand. Since we have only two hands, the distribution of that preference in the population might be expected to follow a simple

dichotomy (right- or left-preference). However, when people are asked to describe their own hand-use preference, a third category commonly appears (often called ambidextrous but more appropriately labeled ambilateral). Furthermore, when asked to report right- or left-hand use for a series of questions about common manual activities, the relative scores of right- to left-hand use across individuals take on the character of a continuous distribution, with a sharp skew in the sample toward use of the right hand. If the answers to each question about manual actions permit ratings from 1 (*always left*) to 5 (*always right*), then the distribution, although skewed, is somewhat less so. Various measures of skill differences between the two

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hands also reveal a continuous distribution with a nontrivial number of individuals exhibiting no difference between hands. Nevertheless, the distribution is always skewed such that more individuals exhibit greater skill with their right than left hand (Annett, 1985; Bryden & Steenhuis, 1991).

Although measures of skill and the self-assessment of handedness are related, there is sufficient disparity to create discrepancies among studies using these different measures. Thus, contemporary estimates of right-hand-use preference vary between 70 to 95% of individuals, depending upon cultural background and the specific criteria used to define right-handedness (Bryden & Steenhuis, 1991; Porac & Coren, 1981). Since hand-use preference, however defined, is continuously distributed in the population, the specific choice of criteria to define right-handedness not only affects the estimates of preference but those estimates also are affected by whether handedness is considered to be a dichotomous character. Many studies that examine the relation of handedness to other variables do not use a continuous measure of handedness, but rather dichotomously classify individuals into right-handed and not right-handed. Obviously, the variability in criteria used for constructing these two classes (from a continuous distribution) contributes to the creation of apparently contradictory evidence about the relation of handedness to other variables and the failure to replicate previous results. One purpose of the present study is to demonstrate the value of using a three- rather than two-category classification of infant hand-use preferences, with right- and left-handedness defined by identical criteria.

Handedness classification procedures also may be evaluated by how well they reflect the factors presumably involved in the causes of handedness. Since handedness in offspring is correlated with that of their parents (e.g., McManus & Bryden, 1992), it seems likely that some genetic factor must be involved in the expression of human handedness. Although a consistent environmental bias (a "right-sided world") likely contributes to the right predominance (Collins, 1975; Porac & Coren, 1981), right-handedness predominates in all cultures (Corballis, 1991) and may have for at least 5,000 years (Coren & Porac, 1977) and perhaps since the Lower Pleistocene era (Toth, 1985). Therefore, it is much more likely that the biases in the social and physical environment were created as a consequence of the right-hand predominance in the population. However, the genealogical data do not support any simple Mendelian model, and consequently, several genetic models have been proposed (Annett, 1985; Corballis, 1997; Levy & Nagylaki, 1972; McManus, 1985). Currently, Annett's

model has received the most attention (e.g., Annett, 1996; Corballis, 1997; McManus, Shergill, & Bryden, 1993).

According to Annett (1972), the "right shift" in the distribution of human handedness is due to a single gene (RS) inherited in a Mendelian fashion. However, the presumptive RS gene does not determine whether a person is right- or left-handed. Rather, it creates a bias toward right-handedness for the majority of individuals who inherit a right-shift gene (RS). When the gene is absent (RS-/-), supposedly random processes during the course of ontogenetic development determine individual handedness. Thus, Annett's model proposes a genetic tendency toward right-handedness but not left-handedness. Left-handedness arises as a consequence of contingent events during development, and may do so even for those with the RS gene. However, left-handedness is more likely to occur in the absence of the RS gene.

In Annett's model, individuals vary from one another along a continuum according to the differences in skill between the left and right hand. Hand-use preference is a secondary consequence of this difference in relative skill. The handedness phenotype is expressed as degrees of preference (on a handedness questionnaire) that are systematically related to performance differences between the two hands (a timed unimanual movement of pegs-into-holes task). For those lacking the gene (RS-/-), the intermanual performance difference is centered on zero, and the proportion of those with a left-hand-use preference will vary between 35 and 50% depending on the specific assumptions of the model (Annett, 1985). The inheritance of the right-shift (RS+) gene shifts that distribution in favor of the right hand, and the gene is estimated to account for 50% of phenotypic variation in handedness (Gilger, 1995). Therefore, based on Annett's model, there are two distinct populations underlying the handedness phenotypes: those who carry the right shift gene (RS+/+ and RS+/-) and those who do not (RS-/-).

Originally, Annett argued that the RS gene was dominant. Consequently, the handedness distribution of those individuals with at least one copy of the gene was as right shifted as the distribution of those with two copies of the gene. Those without the gene were equally divided into right- and left-handers. Recently, Annett (1985, 1995) proposed an additive influence of the RS gene on handedness. Individuals homozygous for RS show stronger right-handedness than those individuals who are heterozygous for RS. Annett (1995) used this additive model to account for the continued presence of left-handers in the population. That is, she proposed that heterozygous individuals

(RS+/-) possess some selective advantage (perhaps in some intellectual capacity and/or brain organization) over homozygous (RS+/+) individuals. Such heterozygous advantage would explain the maintenance in the population of the proportion of presumably disadvantaged individuals with the RS-/- genotype (and, correspondingly, the nontrivial proportion of left-handed individuals).

Since the handedness phenotype reflects three genotypic subpopulations, an individual's manifested hand-use preference does not directly identify the underlying genotype. That is, although the majority of individuals who are RS heterozygous will be right-handed, at least 8% will be left-handed. Thus, phenotypic left-handers may be estimated to be composed of at least 50% of that small proportion of the population without the RS gene, plus a small proportion of those heterozygous for RS, and an even smaller proportion of those that are RS+/+ homozygous. Similarly, phenotypic right-handers will be composed of some RS-/- and RS+/- individuals, but the majority should be RS+/+ individuals.

Although several different heuristics have been used to divide phenotypic handedness distributions so that they represent the two subgroups (those with and those without the RS gene), all have troubling limitations (Annett, 1985, 1995; Bryden & Steenhuis, 1991). Nevertheless, Annett (1996) demonstrated that the estimated proportion of RS-/- depends on how left-handedness is defined. If defined conservatively so that only 2.5% of the sample is left-handed, then RS-/- is estimated to be about 96% of these left-handed individuals. If left-handedness is defined less conservatively so that 35% of the sample is left-handed, then about 47% of these individuals are estimated to be RS-/- whereas 32% are RS+/- and 21% are RS+/+. Since the method of classifying handedness greatly affects the likely presence of the right-shift factor within each category of handedness, another purpose of the present study was to compare and evaluate two different criteria for constructing the categories of infant hand-use preferences. A more conservative classification criterion should provide a more reliable identification of the presence and absence of the right-shift factor in an infant.

It is generally accepted that the RS gene does not directly determine either handedness or cerebral asymmetry (Corballis, 1997). Rather, both of these asymmetries must arise as a consequence of some asymmetrical factor influencing development (Bishop, 1990; Gilger, 1995). Thus, Hopkins and Ronnqvist (1998) argued that if Annett's model is to qualify as a model for the developmental origins of handedness, it must be applied to the distribution of

functional asymmetries purported to be precursors of adult handedness. However, to determine the precursors of adultlike handedness, the age at which an adultlike handedness is attained must be known because precursors can only occur during the period of development preceding that age. Unfortunately, no general consensus has been reached for this age, and it varies between 13 months and 8 years (13 months: Bates, O'Connell, Vaid, Sledge, & Oakes, 1986; 18 months: Gottfried & Bathurst, 1983; 2 years: Giesecke, 1936 and Hildreth, 1949; 3 years: Annett, 1970; after 8 years: Connolly & Elliott, 1972 and Gesell & Ames, 1947). Since longitudinal research of infants beyond 1 year of age reveal that the majority exhibit a consistent right-hand preference across a range of tasks (Archer, Campbell, & Segalowitz, 1988; Bates et al., 1986; Gottfried & Bathurst, 1983), the precursors of adult handedness likely emerge during the infant's first year.

Michel (1998) argued that the infant's supine head-orientation preference during the first 2 months after birth is an early precursor of later infant hand-use preference for apprehending objects. Observation of 150 neonates revealed that their head-orientation preferences were continuously distributed but with a distinct right shift, similar to that reported for adult handedness (Michel, 1981). Moreover, direction (right or left) of supine head-orientation preference predicted direction of hand-use preference for apprehending objects throughout the period from 4 to 18 months after birth (Michel & Harkins, 1986). Therefore, Michel (1998) proposed that hand-use preference for apprehending objects is a developmental precursor for later child/adult handedness, as measured by either skill or preference in tasks involving unimanual and/or bimanual manipulation.

Although these studies reveal a pattern of phenotypic expression of neonatal head-orientation preferences and infant hand-use preferences similar to that of adult handedness, they do not permit identification of the underlying subpopulations predicted by Annett's model. This is in part because distinguishing manual differences in skill versus simple differences in use during the infant's first year is problematic. However, statistical decision criteria may resolve this problem. That is, if one hand has such a high frequency of use when apprehending a large number of objects that the difference between hands is unlikely to have occurred by chance, then this preference may be presumed to reflect an underlying difference between the hands in prehensile skill (Michel, 1998). Maintenance of that "significant" preference of use across several age periods also may be presumed to reflect differences between the hands in manual skill.

Therefore, we applied a latent class model to a corpus of longitudinal data on infant hand-use preferences for apprehending objects, as classified by two different statistical decision criteria, to determine whether the manifest hand-use preferences reflect the underlying subgroups as predicted by Annett's model.

Latent class models assume that the sample observations are drawn from a mixture of qualitatively distinct, internally homogeneous groups of infants. These models are especially useful when it is not possible to identify the group to which a particular subject belongs directly from the observed variables (Clogg, 1995; Stern, Ancus, Kagan, Rubin, & Snidman, 1995), as is the case in the relation between phenotypic handedness and its underlying genotype. Latent class models can incorporate either categorical or continuous measurements. Information about the number of groups in the population is obtained by examining the fit of several latent variables. The present study applies a latent class analysis to a longitudinal sample of data on the hand-use preferences infants exhibited when reaching for and acquiring objects at 7, 9, and 11 months of age to evaluate the two variants (dominance or additive) of Annett's model.

Annett's original model (the dominance variant) predicts that the infant sample will be composed of two groups, those possessing the RS gene (dominated by right-handers) and those without the RS gene (with relatively equal proportions of right- and left-handers). In contrast, the additive variant of Annett's model predicts three underlying groups. One group is composed of those who are homozygous for the RS gene (nearly all of whom are right-handed). Another group is composed of those who are missing the gene (RS-/-), with right- and left-handedness estimated to be either about equal in proportion or distributed 65:35, respectively. A third group is composed of those who are heterozygous (RS+/-), with about 84% expected to be right-handed. In the present study, we assume a three-category classification of infant hand-use preferences (right, left, and no preference) for each of the three assessment ages and compare two different criteria for forming these three categories.

Thus, we use latent class analysis of infant hand-use preferences for acquiring objects at three age periods (7, 9, and 11 months) to determine whether the pattern of infant handedness is consistent with two or three underlying groups as predicted by the two versions of Annett's genetic model. In addition, two different criteria for constructing the three categories of infant handedness will be compared and evaluated for their consequences on the subgroups of infant handedness revealed by the latent class analysis.

## METHOD

### Subjects

One hundred fifty-four infants (75 males, 79 females) were selected from a larger sample of 258 infants who participated in a study of sensorimotor development at the Infant Development Center, DePaul University. All infants had healthy, full-term births (at least 39 weeks of gestation, Apgar score greater than 7 at 5 min, birth weight of at least 3,000 g) after uneventful pregnancies at Columbus Hospital in Chicago. The infants represented a diverse mix of Middle and Eastern European, Central American and other Hispanic, and African American ethnic backgrounds. After receiving a recruitment letter, parents were contacted by telephone to identify those who wanted to participate in the study. If they chose to participate, an informed consent form was sent and their first appointment to visit the Center was set up. Each infant was assessed at 7, 9, and 11 months after their birth date ( $\pm 1$  week). All had two parents living at home with either blue-collar or white-collar occupations. Parents received a stipend of \$10.00 per visit plus free parking. The infants were selected for this study because they provided hand-use data for all three of the hand-use preference assessment age periods. All aspects of this study received Institutional Review Board approval.

### Procedure

Upon arriving at the Center, infants were seated in a highchair that provided postural support and allowed freedom of movement of their hands above the table. The parent was seated behind the infant. In some instances, infants sat on their mothers' laps at a table. A Panasonic 6200 VCR with a split-screen device recorded that infant's actions from an overhead video camera and a camera placed in front of the infant. The experimenter was situated in front of the infant but out of the field of view for both cameras. Handedness was assessed using the procedure described in Michel, Ovrut, and Harkins (1985). This procedure has high test-retest reliability ( $\kappa = .93$ ) and was validated by a high correlation ( $r = .90$ ) to hand-use for acquiring objects during semispontaneous play.

Twenty toys (e.g., plastic rings, rattles, cups) were presented to the infant for a total of 26 presentations for each infant. The toys were selected to be attractive to infants across a wide age range. Nine toys (One was presented twice.) were placed singly in the midline (between the infant's shoulders and in line with the nose) on the table within reaching

distance (The presenter alternated use of his/her right and left hand between the 10 presentations.) Five toys (One was presented twice.) were presented in the midline in the air at the infant's eye level (Again, the presenter's hands were used alternately for the six presentations.) There were two presentations of two identical toys presented in the air, with one in line with the infant's right shoulder and the other in line with the left shoulder. There were four presentations of two identical toys each that were placed simultaneously on the table in line with each of the infant's shoulders. There were four presentations involving two different toys, each placed simultaneously on the table in line with each of the infant's shoulders and the position of the different toys reversed between presentations.

The order of presentation was quasi-random for each infant; these variations in presentation were used to reduce any preference bias that might occur between an infant and specific toys. The experimenter retrieved each toy before the next was presented. To be consistent across the dual and single toy presentations, the experimenter always used both hands when retrieving the toys. Toys were represented later if the infant did not reach to obtain the toy within 20 s after presentation. Each infant provided hand-use data for at least 22 presentations.

The videotapes were coded in real time by raters filling out forms that listed the toys presented during each assessment. Raters identified which hand initially contacted and grasped each specific toy. The tape speed was slowed in the event of a bimanual reach. Interrater reliability based on 25% of the infants was greater than 97%. A hand-use preference score was calculated for each of the three assessment age periods by subtracting the frequency of left-hand use from the frequency of right-hand use for all presentations and dividing the remainder by the square root of the total frequency of right- and left-hand use. This score represents a *z*-score distribution, with positive scores reflecting more right- than left-hand use and negative scores reflecting more left- than right-hand use. These *z* scores were used to classify an infant's hand-use preference as "right" (R), "left" (L), or "no preference" (NP) for each visit. Thus, across the three assessment sessions, infant handedness patterns could exhibit 27 variations from "R, R, R" through "NP, NP, NP" to "L, L, L." Latent class analyses were then applied to these patterns of handedness. Although more than three categories of handedness are possible, latent class models relying on finer categorizations of handedness would have required many additional subjects and additional parameters.

The three categories of handedness were formed from the *z*-scores by one of two procedures. For the less conservative classification Procedure A, a *z*-score greater than +1.0 was identified as a right-hand-use preference for that assessment age period. A score less than -1.0 was identified as a left-hand-use preference for that age period. Scores between  $\pm 1.0$  were described as no preference. For the more conservative classification Procedure B, a *z*-score greater than +1.65 was identified as a right-hand-use preference for that assessment age period. A score less than -1.65 was identified as a left-hand-use preference for that age period. Scores between  $\pm 1.65$  were described as no preference. The  $\pm 1.65$  and the  $\pm 1.0$  *z*-score classification procedures were chosen to be consistent with previous publications assessing infant handedness (cf. Michel, 1998).

Thus, the two classification procedures differ in their definition of an infant's preference based on the relative frequency of right- and left-hand use in the acquisition of objects. Classification Procedure B reduces the expected proportion (as based on Annett's model) of RS-/- individuals who exhibit a right-hand preference to about 3% as compared to the approximately 12% for classification Procedure A (McManus et al., 1993). In addition, classification Procedure B reduces the expected proportion of individuals with at least one RS who exhibit a left-hand preference to about 21% as compared to 45% for classification Procedure A.

For both classification procedures, we applied the latent class analysis to the categorical assignment of handedness instead of the actual *z*-scores to avoid any assumption concerning the distribution of scores within each group. Latent class models are designed to account for the observed responses (patterns of handedness) by postulating a population that is a mixture of several distinct, but internally homogenous groups of subjects. To apply the model, assumptions about the number of groups and a model specifying the distribution of outcomes within each group are required. The basic assumption is that within any group of the (latent) class, the observed responses are independent of one another. If group membership of each infant had been known, the probability that an infant in each group would have exhibited a particular pattern of hand-use preference could have been estimated from the sample population exhibiting that pattern. Since group memberships were unknown, the iterative procedure (Goodman, 1974) was used to estimate the parameters of both a two- and a three-group model based on the categorical classification of the infant's handedness at each of the three age periods.

The iterative procedure is a special case of the so-called EM algorithm (Dempster, Laird, & Rubin, 1977). When the likelihood function of a latent class model has several modes, the estimating procedure converges to one of them. To check the stability of the estimates, the starting values of the model parameters are randomly set and several runs are repeated for the same data. We implemented the iterative procedure for fitting latent class models in S-Plus (Sheu, in preparation). The latent class analysis was repeated under a variety of assumptions about the number of groups, and then the fits of the models were examined. Because latent class models are not nested models, a chi-square test cannot be used to determine whether the two-class model provides a better fit than that of the alternative three-class model (Stern et al., 1995). Therefore, we evaluated the models based on the stability of the parameter estimates and whether the estimates have clear interpretations. Consistent with our hypotheses, we examined both the two-class model and the three-class model separately for each of the two handedness-classification procedures.

## RESULTS

Table 1 shows the number of infants in each of the 27 possible combinations of infant hand-use preference (as classified by Procedure A with  $z$ -scores of  $-1$  and  $+1$  defining the three categories of handedness) for the three assessment ages. A latent class model was applied to these data with the assumption that there were two groups of infants. Each of the observed variables (7, 9, and 11 months) was assumed to have a multinomial distribution within each of the two groups of infants. From the perspectives of both the

dominance and additive variants of Annett's model, it can be assumed that when an infant carries the RS gene, then that infant has a high probability of exhibiting a right-hand-use preference at each of the assessment ages.

The results of the two-group estimation procedure are shown in Table 2. The two-class model examines the dominance variant of Annett's model in which two groups underlie the data (those with and those without RS). Over 61% of the infants are in one group characterized by a high proportion of infants with a right-hand-use preference at all three assessment ages and few with a left hand-use preference. This accords well with one estimate of the incidence of the RS gene in the population (0.57; Annett, 1985) but not with another (0.81; Annett, 1996). In addition, since this classification procedure does permit about 45% of those with left-handedness to have at least one RS gene, the numbers of left-handed infants at 7 months (5 infants), 9 months (15 infants), and 11 months (6 infants) is below the expected misclassification rate. Therefore, we may consider this group to be composed nearly completely of individuals with the RS gene.

About 38% of infants are in a second group. This group is characterized by a relatively equal proportion of infants manifesting any of the three hand-use preference classes (e.g.,  $\chi^2(2) = 5.0$ ,  $p > .10$  for 9-month data) until the oldest age period when they seem to divide into relatively equal proportions with a left- or a right- hand-use preference,  $\chi^2(2) = 18.0$ ,  $p < .01$ . Again, if we assume that this group represents RS-/- infants, then this accords well with Annett's prediction that about 50% of those without the RS gene will develop left-handedness. This classification procedure predicts that about 12% of right-handed

**Table 1. Distribution of Hand-Use Preference Across the Three Age Periods for Classification Procedure A**

7-Month Preference	9-Month Preference	Hand-Use Preference at 11 Months		
		Right	No Preference	Left
Right	Right	26	15	3
Right	No preference	9	5	5
Right	Left	7	5	2
No preference	Right	16	3	2
No preference	No preference	5	5	2
No preference	Left	9	3	5
Left	Right	4	2	3
Left	No preference	7	0	2
Left	Left	5	1	5

**Table 2. Parameter Estimates for Two-Class Latent Models for Hand-Use Preference Classification Procedure A (Smallest  $\chi^2 = 13.19994$  in 100 Repeated Runs)**

	Class (Group) 1	Class (Group) 2
Proportion of infants in class	0.6167	0.3833
7-Month right preference	0.6766	0.2159
7-Month no preference	0.2745	0.3715
7-Month left preference	0.0489	0.4126
9-Month right preference	0.6184	0.2248
9-Month no preference	0.2207	0.3225
9-Month left preference	0.1609	0.4527
11-Month left preference	0.5807	0.5226
11-Month no preference	0.3599	0.0816
11-Month right preference	0.0593	0.3959

infants are RS-/- . This means that we might expect 9 infants at both 7 and 9 months of age in this group to exhibit right-handedness, which is not significantly different from the 13 right-handed infants in this group at each of these two ages. Since both the smallest and the largest  $\chi^2$  for 100 repeated runs differed only slightly (difference = 0.00004), the two-class estimates seem to be quite reliable, and the classes seem to match Annett's model. Unfortunately, Group 1 only captures 83% of right-handers at 7 months, 82% of right-handers at 9 months, and 64% of right-handers at 11 months. Therefore, right-handedness at any one of these ages is a relatively weak predictor of membership in Group 1 and presumably of the RS+ genotype.

Table 3 shows the results of the estimation procedure for the three-class model for the data associated with classification Procedure A. The three-class model examines the additive variant of Annett's model in which three groups (RS+/, RS+/-, RS-/-) are predicted to underlie the phenotypic data. About 32% of the infants are in one group characterized by a high proportion of infants with a right-hand-use preference at all three assessment ages and none with a left-hand-use preference at 7 and 11 months. The number of left-handed infants at 9 months in this group is much less than that predicted by the misclassification rate associated with Procedure A. Therefore, the evidence from this group is consistent with the notion that it is composed of RS+/+ infants.

A second group comprises some 53% of infants and is characterized by a shifting distribution of preferences. At 7 months,  $\chi^2(2) = 7.9, p < .05$ , and 11 months,  $\chi^2(2) = 11.9, p < .01$ , there is a relatively greater proportion of right-handers whereas at

9 months there is a greater proportion of infants with no preference,  $\chi^2(2) = 10.7, p < .01$ . At all three ages, the proportion of left-handers is rather similar to that predicted by the misclassification rate associated with Procedure A. Therefore, the evidence from this group is consistent with the notion that it is composed of infants with at least one RS gene.

The third group (about 14% of infants) exhibits a fairly stable (throughout the three age periods) proportion of left-handed infants representing nearly half of the group. The "no preference" infants seem to acquire a "right preference" by 11 months. Although at no age is the number of right-handed infants greater than that which is expected by the misclassification rate associated with Procedure A, the number of left-handed infants is much smaller than predicted (Annett, 1996, Table 1). Therefore, the evidence from this group seems consistent with the notion that it is composed of infants with the RS-/- genotype.

In 1996 (Table 1), Annett derived the following genotype proportions for the human population: RS+/+ = .3242, RS+/- = .4904, and RS-/- = .1854. Comparison of these proportions with those obtained by the latent class analysis reveals no significant difference,  $\chi^2(2) = 1.99, p > .10$ . Therefore, classifying infant hand-use preferences by Procedure A seems to capture the predicted distribution of the three right-shift genotypes in the population. However, the pattern of handedness development revealed in the presumptive RS+/- and RS-/- groups does not match that predicted by Annett's model. In addition, only 49% of the right-handed infants at 7 months, 57% of right-handed infants at 9 months, and 38% of right-handed infants at 11 months are captured by Group 1. Therefore, right-handedness at any of these ages cannot be used to predict membership in Group 1 or the presence of the RS+/+ genotype. However, at 7 months, no right-handers are in Group 3; at 9 months, only 7% of right-handers are in Group 3; and at 11 months, only 13% of right-handers are in Group 3. Thus, right-handedness, as determined by Procedure A, is a fairly good predictor of membership in Groups 1 or 2. Since both the smallest and the largest  $\chi^2$  for 100 repeated runs distinctly differed (difference > 2.67), the three-class estimates may not be reliable.

Table 4 shows the number of infants in each of the 27 possible combinations of infant hand-use preference (as classified by Procedure B with z-scores of -1.65 and +1.65 defining the three categories of handedness) for the three assessment ages. These data were examined by latent class analysis.

Table 5 shows the results of the estimation procedure for the two-class model (Annett's dominance

**Table 3. Parameter Estimates for Three-Class Latent Models for Hand-Use Preference Classification Procedure A (Smallest  $\chi^2 = 8.422$  in 100 Repeated Runs)**

	Class 1	Class 2	Class 3
Proportion of infants in class	0.3239	0.5333	0.1432
7-Month right preference	0.755	0.479	0.0001
7-Month no preference	0.2423	0.2938	0.5359
7-Month left preference	0.0027	0.2272	0.464
9-Month right preference	0.824	0.3157	0.2259
9-Month no preference	0.0	0.4871	0.0
9-Month left preference	0.176	0.1972	0.7741
11-Month right preference	0.6576	0.5161	0.4916
11-Month no preference	0.3424	0.2549	0.0478
11-Month left preference	0.0	0.229	0.4636

**Table 4. Distribution of Hand-Use Preference Across the Three Age Periods for Classification Procedure B**

7-Month Preference	9-Month Preference	Hand-Use Preference at 11 Months		
		Right	No Preference	Left
Right	Right	16	13	0
Right	No preference	10	8	6
Right	Left	2	4	1
No preference	Right	16	9	2
No preference	No preference	11	13	5
No preference	Left	5	6	4
Left	Right	3	2	1
Left	No preference	7	3	0
Left	Left	2	3	2

variant) for the data associated with the more conservative classification Procedure B. Nearly 41% of the infants are in one group characterized by a greater proportion of infants with a right-hand-use preference at all three assessment ages and virtually no infants with a left hand-use preference. The number of left-handed infants at 7 months is similar to that predicted to be misclassified by Procedure B. Therefore, the evidence from this group is consistent with the notion that it is composed entirely of infants who possess the RS gene. However, at 7 months, only 55% of right-handers are in Group 1; at 9 months, 81% of right-handers are in Group 1; and at 11 months, only 53% of right-handers are in Group 1. Therefore, right-handedness, as determined by Procedure B is not a good predictor of membership in Group 1.

Nearly 60% of infants are in the second group. This group is characterized by a relatively greater propor-

tion of infants manifesting no hand-use preference at 7 months,  $\chi^2(2) = 13.5, p < .01$ , and 9 months,  $\chi^2(2) = 23.9, p < .01$ . By 11 months, however, there is a relatively equal proportion of infants exhibiting any of the three classes of hand-use preference,  $\chi^2(2) = 4.3, p > .1$ . The number of right-handed infants at all three age groups is much greater than is predicted by the misclassification of RS-/- infants associated with Procedure B. Therefore, the evidence from this group is not consistent with the notion that it is composed of just RS-/- infants. Since both the smallest and the largest  $\chi^2$  for 100 repeated runs differed only slightly (difference = 0.00001), the two-class estimates seem to be quite reliable.

Table 6 shows the results of the estimation procedure for the three-class model for the data associated with classification Procedure B. About 36% of the infants are in one group characterized by a greater proportion of infants with a right-hand-use preference at all three assessment ages and virtually none with a left-hand-use preference. The three left-handed infants at 7 months is lower than the misclassification rate associated with Procedure B. Therefore, the evidence of this group is consistent with the notion that it is composed entirely of infants with an RS+/+ genotype. However, at 7 months, only 48% of right-handed infants are in Group 1; at 9 months, 89% of right-handed infants are in Group 1; and at 11 months, only 46% of infants are in Group 1. Therefore, right-handedness, as determined by Procedure B, at these ages is not a good predictor of Group 1 membership or of the presumed RS+/+ genotype.

A second group, representing some 53% of infants, has a larger-than-expected proportion of infants with a left-hand-use preference at all three ages than would be expected by the misclassification associated with

**Table 5. Parameter Estimates for Two-Class Latent Models for Hand-Use Preference Classification Procedure B (Smallest  $\chi^2 = 10.50048$  in 100 Repeated Runs)**

	Class (Group) 1	Class (Group) 2
Proportion of infants in class	0.4068	0.5932
7-Month right preference	0.5247	0.2969
7-Month no preference	0.4055	0.4992
7-Month left preference	0.0698	0.2039
9-Month right preference	0.7934	0.1346
9-Month no preference	0.2066	0.5479
9-Month left preference	0.0	0.3175
11-Month right preference	0.6148	0.3665
11-Month no preference	0.3852	0.4046
11-Month left preference	0.0	0.2299

**Table 6. Parameter Estimates for Three-Class Latent Models for Hand-Use Preference Classification Procedure B (Smallest  $\chi^2 = 6.9$  in 100 Repeated Runs)**

	Class 1	Class 2	Class 3
Proportion of infants in class	0.3576	0.5284	0.1139
7-Month right preference	0.5265	0.3809	0.0
7-Month no preference	0.4088	0.4591	0.6342
7-Month left preference	0.0647	0.16	0.3658
9-Month right preference	0.9999	0.0	0.3947
9-Month no preference	0.0	0.7741	0.0
9-Month left preference	0.0	0.2259	0.6054
11-Month left preference	0.6021	0.4248	0.2434
11-Month no preference	0.3979	0.405	0.3494
11-Month right preference	0.0	0.1703	0.4072

Procedure B. Therefore, the evidence of this group is not consistent with the notion that it is composed of infants entirely with the RS+/- genotype. At 7 and 9 months, there is a surprisingly large proportion of infants with “no preference.” At 11 months, the proportion of infants with no preference is about equal to the proportion of infants with a right-hand-use preference, but the proportion of infants with left-handedness is significantly greater than would be expected by misclassification.

The third group (about 11% of infants) begins at 7 months with no infants with a right-hand-use preference and most with no preference. By 9 months, all infants have a hand-use preference, with the majority showing a left preference. At 11 months, the distribution of infants across the three handedness categories does not differ from equal,  $\chi^2(2) = 0.8, p > .10$ . However, the number of right-handed infants at 9 and 11 months is much larger than that predicted by the misclassification associated with Procedure B. In addition, the number of left-handed infants in this group at all three ages is much smaller than predicted (Annett, 1996). Therefore, the evidence from this group is not consistent with the notion that it is composed of infants with the RS-/- genotype. However, at 7 months, no right-handers are in Group 3; at 9 months, only 11% of right-handers are in Group 3; and at 11 months, only 6% of right-handers are in Group 3. Thus, right-handedness, as determined by Procedure B, is a fairly good predictor of membership in Groups 1 or 2.

Again, the distribution of infants in the three groups is not significantly different,  $\chi^2(2) = 5.8, p > .05$ , from the distribution of the three genotypes predicted by Annett (1996, Table 1). Since both the smallest and the largest  $\chi^2$  for 100 repeated runs distinctly differed (difference > 2.8), the three-class estimates may not be reliable.

The more conservative of the two classification procedures (B) seemed to shrink by a third the proportion of infants presumably influenced by a right-shift factor (cf. Tables 2 and 5). Therefore, it might be expected that the least conservative classification procedure would match more closely the relatively high frequency of the RS gene in the population (about 82%), as predicted by Annett (1996). To test whether the least conservative procedure for classifying infant handedness could capture the predicted RS gene frequency better, infants were classified as right- or left-handed based simply by the sign of their z-score at each age (positive = right; negative = left), and another two-group latent class analysis was conducted. A three-class model would be inappropriate for this data. For this classification procedure, Table 7 shows the number of infants in each of the

**Table 7. Distribution of Hand-Use Preference Across the Three Age Periods for the Simple Classification Procedure**

7-Month Preference	9-Month Preference	Hand-Use Preference at 11 Months	
		Right	Left
Right	Right	65	8
Right	Left	22	11
Left	Right	19	6
Left	Left	15	7

eight possible combinations of infant hand-use preference for the three ages.

Table 8 shows the results of the estimation procedure for the two-class model. Since both the smallest and largest  $\chi^2$  for 700 repeated runs differed only slightly (difference = 0.0000), the two class estimates seem to be quite reliable. Slightly more than one third of the infants are in a group characterized by an overwhelming predominance of right-hand-use preference at all three ages. The evidence from this group is consistent with the notion that there is some right-shift factor prompting a consistent right bias to the infant’s hand-use preference for apprehending objects. Unfortunately, this proportion does not match that expected if the RS gene was dominant or even if it provided an additive effect on handedness.

The second larger group of infants is characterized by a much more variable distribution of infant hand-use preferences. The distribution of right- and left-handedness is not significantly different from equality at both 7 months,  $\chi^2(1) = 2.98, p > .10$ , and 9 months,  $\chi^2(1) = 1.25, p > .10$ , but right-handedness dominates at 11 months,  $\chi^2(1) = 11.2, p < .01$ . The proportion of infants in this group (0.63) appears to be consistent with the proportion of infants predicted by Annett

**Table 8. Parameter Estimates for Two-Class Latent Models for Hand-Use Preference Classification Using the Simple Procedure**

	Class (Group) 1	Class (Group) 2
Proportion of infants in class	0.3666	0.6334
7-Month right preference	0.5247	0.2969
7-Month left preference	0.0698	0.2039
9-Month right preference	0.7934	0.1346
9-Month left preference	0.0	0.3175
11-Month right preference	0.6148	0.3665
11-Month left preference	0.0	0.2299

(1996) to have no more than one RS gene (0.68). Clearly, both right- and left-handedness represent greater proportions of the population of this group than expected. It also appears that for this group of infants, hand-use preference may gradually emerge during infancy with right-handedness predominating.

This nonconservative classification procedure shows that the difference between classification Procedures A and B in the proportions of infants apparently demonstrating the influence of a right-shift factor is not simply the result of Procedure B's more conservative assignment of hand-use preferences to infants.

## DISCUSSION

In general, the results provide overwhelming support for the notion that there is some proportion of infants for whom the distribution of their hand-use preferences for apprehending objects is strikingly shifted toward a right bias. In every latent class analysis, a group was identified in which the infants manifested a consistency of right hand-use throughout the later half of the infant's first year. Typically, this group consisted of about one third of the population. The presence of a right-shift factor underlying infant hand-use preference for apprehending objects may be considered additional evidence that this preference is a precursor of adult handedness. Therefore, Annett's model may be a model for the development of handedness (cf. Hopkins & Ronnqvist, 1998).

Although the specific criteria for defining infant hand-use preferences for apprehending objects influenced the groups identified by latent class analysis, whichever criterion was used, the two-group models provided much more reliable estimates than the three-group models. In addition, the less conservative classification procedure (A) provided the best evidence for Annett's model. The two-group analysis of this classification procedure identified a proportion of infants (equivalent to that predicted by Annett, 1985) who apparently share a factor that greatly increases the probability that they will exhibit a right-hand-use preference throughout the three age periods. The second group exhibited a pattern of development of hand-use preferences also predicted by the dominance variant of Annett's model. That is, the hand-use preferences of these infants seemed to develop into roughly equal proportions of right- and left-handedness. Therefore, classification Procedure A provided support for the dominance variant of Annett's model.

Unfortunately, the three-group analyses for both classification procedures were less reliable than the

two group analyses. Therefore, this study does not allow us to choose between the dominance and the additive variants of Annett's model. Nevertheless, although less reliable, the three-group latent class analysis of infants classified by Procedure A also generally supported the additive variant of Annett's model. Again, there is clearly a group of infants apparently sharing a factor that greatly increases the probability that they will exhibit a right-hand-use preference throughout the three age periods. Also, the proportion of infants in this group is quite similar to the proportion of individuals predicted to have the RS+/+ genotype (Annett, 1996).

Indeed, the proportions of infants in each of the three groups identified by the latent class analysis closely matched the proportions of individuals predicted, by Annett, to have each of the three genotypes. A second latent group was composed of a proportion of infants similar to that predicted by Annett to have the RS+/- genotype. However, the distribution of their hand-use preferences at each of the three ages may be inconsistent with Annett's predictions. Although the infants in this group appear to be exhibiting a pattern of development in which right-handedness may be increasing, the proportion of left-handedness is much greater than may be predicted from Annett's model. Perhaps, as these infants develop, they will become more right-handed and the proportion of left-handed infants will shrink. That would mean that infants with the RS+/- genotype undergo a different pattern of development from those with a RS+/+ genotype. That is, those with the RS+/+ genotype develop handedness very early whereas those with the RS+/- genotype develop handedness much later.

Although Annett's additive variant does allow for the influence of more developmentally contingent influences on the handedness of the RS+/- genotype, there is nothing in the theory that would suggest that these developmental contingencies would gradually reduce left-handedness and increase right-handedness. The presence of the right-shift factor itself should do that. However, perhaps the RS+/- genotype permits a greater influence of social influences on handedness development. Certainly, manual play with caretakers can affect the strength of an infant's hand-use preference, most often weakening a left preference and strengthening a mild right preference (Michel, 1992). If increased social susceptibility is characteristic of this group, then it might be expected that the left-handers would gradually weaken their hand-use preference and the others would gradually develop a right-hand-use preference as they interact with a right-biased world composed of mostly

right-handed companions. Some consequences of this notion will be discussed later.

Although the proportion of infants in the third latent group matched the proportion of individuals predicted to have the RS-/- genotype, the distribution of handedness at all three ages was not consistent with predictions. This group had the highest proportions of left-handed infants at all three ages, as would be predicted if they represented the RS-/- genotype, but they had more right-handed infants than would be predicted (Annett, 1996). However, the pattern of development is somewhat more consistent with Annett's earlier suggestion (1972) that individuals with RS-/- genotype tend to manifest a more even distribution of handedness.

One purpose of the present study was to examine the value of using two different criteria for defining infant hand-use preferences. Applying the two-group latent class analysis to the more conservative classification Procedure B identified a group of infants for whom right-handedness predominated at all three ages and in which there was virtually no evidence of left-handedness. We can be fairly certain that this group was composed almost entirely of infants with the right-shift factor. The other group exhibited a pattern of development somewhat similar to that predicted by Annett's model. However, the distribution of infants in each of the two groups did not match that predicted by Annett's model—there were just too many right-handed infants in the second group to consider this group to be composed of RS-/- infants.

As with classification Procedure A, the proportions of infants in each of the three groups identified by the latent class analysis of data defined by classification Procedure B closely matched the proportions of individuals predicted, by Annett, to have each of the three genotypes. Again, there was a group with a clear right-hand-use preference that can be considered to represent infants with the RS+/+ genotype. Another group showed a pattern of handedness development that is somewhat consistent with Annett's notions about infants with the RS-/- genotype. However, the number of left-handed infants in this group is smaller than that predicted by Annett's (1996) recent estimate. The third group (presumably representing infants with the RS+/- genotype) has a somewhat larger-than-predicted proportion of left-handers. Nevertheless, consistent with the analysis of Procedure A, most of the infants in this presumptive RS+/- group may be developing right-handedness more slowly than those in the presumptive RS+/+ group.

Too often, investigators have employed a simple difference in use between the hands as the sole means of defining an infant's handedness. However, both

classification Procedures A and B, when compared to the procedure of any difference of use between the hands, greatly increased the probability that a right-hand-use preference identified an infant with a right-shift factor. Indeed, the more conservative classification procedure (B) assures greater identification of infants with and without the right-shift factor. Therefore, if the investigator is using handedness to identify a right-shift underlying factor which affects hemispheric specialization, among other asymmetries, then a handedness classification procedure must be used which assigns handedness via a statistical decision criterion that permits a third "no preference" class.

Although this study involved the largest sample of longitudinal data on infant handedness collected by using an assessment procedure with defined validity and reliability and with a means for estimating misclassification of handedness, the sample size was too small for adequate analysis with a three-class latent model. Hence, the identification of the three groups of infants may not be reliable. Nevertheless, this study demonstrated the value of using latent class analyses on longitudinal data for identifying factors underlying phenotypic expression of infant handedness. Indeed, the latent class analysis shows that there are clearly two separate groups of right-handed infants, those with and those without a right-shift bias. However, if infant handedness is to be understood better, studies will require very large samples of infants, assessed many more times than three, using an assessment procedure that creates reliable and valid definitions of right- and left-handedness. Studies that do not meet these requirements contribute little to our knowledge of handedness development or its relation to other characteristics. Moreover, similar studies will need to be conducted on other potential infant precursors of adult handedness (supine head-orientation preference, object manipulation hand-use preferences, role-differentiated hand-use preferences).

Michel (cf. 1998) has argued that the right-shift factor promotes a rightward bias in neonatal supine head-orientation preference (SHOP). The direction of SHOP generates differences between the hands for eye-hand coordination, proprioception, and tactile-mouth experiences. These differences in experience, in turn, promote hand-use preferences for apprehending objects. The hand-use preferences for apprehending objects concatenate developmentally into general hand-use preferences for manipulation and handedness. The present study does support (given the evidence of the right-shift groups revealed by the latent class analyses) the proposal that infant hand-use preference for apprehending objects is a developmental precursor of adult handedness.

The results also provide some insight into Annett's (1995) hypothesis that the right-shift factor reflects a genetic balanced polymorphism with heterozygote advantage. Annett has used differences in the acquisition of reading as evidence for the heterozygotic advantage. She has argued that RS+/+ individuals manifest reading difficulties, but without deficits in phonological memory for words. In contrast, RS-/- individuals manifest reading difficulties plus poor phonological memory for words. Heterozygous individuals do not manifest reading difficulties. However, reading acquisition and the other phenotypes (e.g., mathematical ability) that Annett (1995) examined for evidence of heterozygous advantage would be opaque to natural selection. That is, it is difficult to imagine how individual differences on these cognitive tasks could affect differential reproduction (natural selection).

Given the importance of social behavior in human evolution (Caproael, Dawes, Orbell, & van de Kragt, 1989; Humphrey, 1976), it is likely that natural selection operated to increase susceptibility to social influences during development. Therefore, if RS+/+ individuals are more susceptible to self-generated experiences initiated with the SHOP and if heterozygous RS individuals are generally more susceptible to social influences during development, then it is not too difficult to see how this might be favored by selection pressures during human evolution.

Increased susceptibility to social influences during development for a range of behavioral skills (e.g., manual dexterity and general motoric deftness to emotional regulation, cognitive flexibility, interpersonal proficiency, etc.) is the type of phenotypic manifestation on which natural selection can operate. Indeed, the selection-opaque phenotypes that Annett found to be associated with handedness may be related to increased susceptibility to social influences during development. After all, it is a common observation that children who do well in school usually have a heightened sense of social responsibility and tend to conform more to social norms and the values of their family and community.

Therefore, the discovery in the present data of a group presumptively composed of heterozygous infants, that seemed to be acquiring a right handedness but more slowly than the "right-shift" group, is exciting. If these infants are more susceptible to social influences in the development of their handedness, then that may be evidence of a greater susceptibility to social influences in the development of a wider range of abilities. That greater susceptibility to social influences, if associated with the heterozygous (RS+/-) genotype, would be evidence of a

heterozygous advantage that would lead to a balanced polymorphism and the nontrivial proportion of left-handedness in the human population. Clearly, this is an issue in handedness development that requires much more research attention than it has received.

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